Innovation under cap-and-trade programs

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Policies incentivizing the private sector to reach its innovative potential in "clean" technologies are likely to play a key role in achieving climate stabilization. This article explores the relationship between innovation and cap-and-trade programs (CTPs)—the world's most prominent climate policy instrument—through empirical evidence drawn from successful CTPs for sulfur dioxide and nitrogen oxide control. The article shows that before trading began for these CTPs, analysts overestimated the value of allowances in a pattern suggestive of the frequent a priori overestimation of the compliance costs of regulation. When lower-than-expected allowance prices were observed, in part because of the unexpected range of abatement approaches used in the lead-up to trading, emissions sources chose to bank allowances in significant numbers and reassess abatement approaches going forward. In addition, commercially oriented inventive activity declined for emissions-reducing technologies with a wide range of costs and technical characteristics, dropping from peaks before the establishment of CTPs to nadirs a few years into trading. This finding is consistent with innovators deciding during trading that their research and development investments should be reduced, based on assessments of future market conditions under the relevant CTPs. The article concludes with a discussion of the results and their implications for innovation and climate policy.

climate change | emissions trading | technological change | invention | clean technology

Facilitating innovation in "clean" technologies may be the key to achieving climate change stabilization without dampening economic productivity. Theory and experience indicate, however, that the private sector—apt to be the most significant source of this innovation—will not reach its full innovative potential without well-considered public policies. The pollution market failure involved in greenhouse gas (GHG) emissions implies that the development of emissions-reducing technologies will have less private value than the societal optimum. The market failure associated with innovators' difficulty in fully appropriating returns to research and development (R&D) investments—because of imitation and spillover, for example—implies that private incentives to innovate in clean technologies will be suboptimal. Another drag on private sector innovation stems from the trouble that capital markets and firms regularly have in predicting the risks and rewards of R&D investments, which can have uncertain outcomes and lengthy payback periods. Finally, there are significant challenges involved in displacing existing "dirty" technologies, which benefit from cost and performance advantages that accrue through the use of a technology over time, as well as from network externalities and the human reluctance to abandon sunk costs.

Addressing the pollution market failure should spur demand for clean technology and related private sector innovation (see ref. 1 for an introduction to policies exerting a "demand-pull" on clean technology innovation). Emissions standards, taxes, and trading are relevant climate policy instruments that are currently in place or under consideration for use somewhere in the world.

Cap-and-trade programs (CTPs, a form of emissions trading) are the demand-pull climate policy instrument with the largest economic scope in the world today, primarily because of current implementation in the European Union Emissions Trading Scheme (EU-ETS) and the Regional Greenhouse Gas Initiative (RGGI) in the northeast and mid-Atlantic region of the United States. In addition, a number of significant economic areas (e.g., California, Australia, etc.) are also in the process of initiating CTPs. In the most basic form of CTP, policy-makers set a cap on the quantity of permissible emissions and distribute "allowances" to emissions sources that collectively sum to the cap. If sources can reduce emissions cheaply on a relative basis against sources with different marginal abatement costs, they can sell excess allowances at whatever price the market will bear. CTPs can vary significantly in operation, however, based on policy design approaches to: cap stringency, predictability, and adaptiveness; source coverage; enforcement and market oversight; allowance allocation; allowance price restrictions; intertemporal allowance transfer (e.g., the "banking" of excess allowances for future use by current polluters and the "borrowing" of allowances from the future for current compliance); and so forth. Additional complications arise from CTP interactions with existing energy and environmental policies and from the permeability of the boundaries of capped regions (e.g., reductions in a capped region can "leak" emissions into uncapped regions if polluting activities shift there, or policy-makers may decide to count emissions reductions in uncapped areas or economic sectors as "offsets" for unrealized emissions reductions within a capped region or sector). Although it is not yet clear how successful current CTPs for GHGs will be, past CTPs for the control of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions from the heavily emitting electric power sector appear to have fulfilled the fundamental promise of the instrument, which is quantifiable pollution reductions achieved through a flexible approach to compliance that is politically acceptable and keeps societal costs low.

CTPs have several attributes that support clean technology innovation. CTPs define the potential payoffs for R&D investments by innovators through their allowance clearing prices, which set the bar for clean technology adoption by emissions sources (note that for many clean technologies, the main innovators are not the major emissions sources; see *SI Text, Technical Details*). CTPs also provide the policy stringency and timing predictability that case study research consistently points to as key to the support of innovation (2) through their typical design, which involves targets of increasing stringency implemented over multiyear phases. These attributes can manifest in other demand-pull instruments in different forms, however, and no emissions-reducing policy instrument is unambiguously superior in its incentives for innovation (3).

A unique aspect of CTPs is the variability of the price signal they provide, and it is not well understood what the effect of this

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is on the inherently uncertain innovation process. Allowance prices are unknown before trading begins and change as CTPs operate (the initial phases of Australia's CTP will be an exception). In addition, studies have noted that allowance prices are likely to drop when marginal abatement costs fall with technology adoption by a subset of early-mover emissions sources (e.g., refs. 3–5); as a result, later-moving emissions sources may face reduced incentives to adopt similar new technologies. The corollary for innovators is that early clean technology sales have the potential to cannibalize the later market, thereby reducing incentives for sustained R&D investments. This effect will presumably be either tempered or strengthened by the degree of credibility and relative stringency of future caps, as determined both directly by statute and indirectly through such details of trading operations as allowance banking and the use of offsets to meet compliance obligations (for more on innovation and long-term targets, see ref. 6).

This article employs empirical evidence to clarify our understanding of the relationship between CTPs and the innovation process. The next section discusses the rationale behind selecting certain CTPs, clean technologies, and aspects of the innovation process for study. The following section presents the results of a synthesis of new data and what reviews (e.g., refs. 7–10) have characterized as the small literature that assesses, ex post, the innovation response to CTPs. The article concludes with a discussion of the results and their implications for climate policy and innovation.

Background

Two CTPs were selected for this study. First was Title IV, the two-phase national CTP for SO_2 emissions in the United States that was initiated in the Clean Air Act Amendments (CAA) of 1990, with its second phase concluding at the end of 2010. Second was the Ozone Transport Commission NO_x Budget Program (the OTC CTP) and its virtually seamless replacement and expansion, the NO_x Budget Trading Program under the Environmental Protection Agency (EPA) NO_x State Implementation Plan (SIP) Call (the NBP CTP; the paired CTPs are collectively titled here the OTC/NBP). The OTC/NBP was a seasonal and regional CTP for NO_x emissions in the United States that was established in 1995, with trading beginning in 1999, the cross-program transition occurring in 2003, and the program effectively concluding in 2008. The *SI Text, Policy Context* contains a detailed treatment of the design and implementation of Title IV and the OTC/NBP, including a discussion of the legal and regulatory context that preceded and followed them, while the *SI Text, SO_2 and NO_x Emissions* details relevant reductions over time. Note that Title IV and the OTC/NBP are considered two of the world's most successful examples of the implementation of the CTP instrument, which makes understanding their connection to innovation of particular interest.

Studying Title IV and the OTC/NBP in this context has methodological advantages. Both CTPs have sufficiently long operations for empirical appraisal regarding the long-term, unpredictable phenomenon of innovation. The two CTPs control very different pollutants, which alleviates some of the concern about case overspecificity that can arise in empirical policy research. In addition, the two CTPs are generally comparable in terms of design to most GHG CTPs that are currently operating or preparing for trading (e.g., EU-ETS, RGGI, California), or have received serious legislative consideration, such as the CTP that passed one United States legislative chamber in June 2009. Their geographic scope is similar, for example, with the OTC/NBP affecting the same states as RGGI, as well as several others, and Title IV affecting the full United States, an economic area akin to that covered by the EU-ETS. Their primary sectoral scope is the same (coal-fired electric power plants). For allowance price uncertainty management, like most GHG CTPs, both CTPs rely on allowance banking (albeit with more restrictions under the OTC/NBP than Title IV) rather than *de jure* price ceilings and floors (Australia's first 3 y of flexible carbon pricing will be an exception). The two CTPs are not perfectly comparable with GHG CTPs, however. For example, they do not include a role for borrowing allowances from future years, nor do they have a role for offsets because of the nature of the pollutants they control. Furthermore, although GHG CTPs generally include at least a limited role for the auctioning of allowances—providing a price discovery mechanism, among other benefits—this was true of Title IV but not the OTC/NBP.

Like most CTPs, both Title IV and the OTC/NBP had relatively modest initial caps, established in advance of trading, which increased in stringency at set intervals over time, with applicability to a larger set of sources in later time periods. Title IV's trading phases were announced in 1990: Phase I, which operated in 1995–1999, applied a modest cap to 263 existing electric generating units; Phase II, which operated in 2000–2010, applied a cap equivalent to an emissions rate established in 1971 to about 2,500 existing units. The OTC/NBP's trading phases were more uncertain, however. As originally established in 1994, the OTC CTP had three phases. Phase I, which began on May 1, 1995, did not involve trading, but instead applied year-round, region-wide, "reasonably-available control technology" (RACT) emissions standards—first established for ozone nonattainment areas—to large stationary sources in the OTC region of the northeast and mid-Atlantic states. Phase II, which began on May 1, 1999, established a nine-state CTP in the OTC states during the summer ozone season of May to September, with trading allowed year-round. Phase III, which was supposed to begin on May 1, 2003, tightened earlier caps. Coincidental with the start of Phase III, however, the EPA established the NBP CTP, which superseded Phase III and expanded its scope to include non-OTC states (for which litigation delayed implementation).

Emissions sources could meet caps under Title IV, the OTC/NBP, and GHG CTPs using several approaches, including the purchase of allowances and the following abatement strategies:

Fuel modification: This strategy involves retaining the existing generation process, but switching to lower-emitting fuels. For SO_2 control, combusting coals that are either naturally lower-sulfur or "cleaned" of sulfur at preparation plants is a low-cost, effective way to achieve modest levels of abatement. For NO_x control, however, combusting lower-nitrogen coals has less benefit because it only impacts the oxidation of nitrogen in the fuel, rather than the reaction of molecular nitrogen and oxygen in the combustion air.

Combustion modification: This strategy involves altering the combustion process to achieve lower emissions. A prominent NO_x example is modifying combustion heat and oxygen to achieve modest levels of control at relatively low cost [e.g., low-NO_x burners (LNBs)]. For SO_2, sorbent injection, which operates on different principles, could be considered a similarly inexpensive, modestly effective, but less prominent control technology. Note that modification options that increase power plant efficiency may have abatement advantages that cut across carbon dioxide (CO_2), SO_2, and NO_x control.

Postcombustion control: This strategy involves controlling emissions after combustion, often with large, complex, expensive systems that provide high-performance emissions reduction. Postcombustion control technologies for SO_2, NO_x, and CO_2 include flue gas desulfurization (FGD), selective catalytic reduction (SCR), and carbon capture and storage, respectively. Note that carbon capture and storage is relatively immature and involves a more complex, uncertain system for managing captured pollutants than the other technologies.

Demand reduction: This strategy involves reducing utilization of high-emitting generation facilities, typically in exchange for increased adoption of other abatement strategies or energy-efficient technologies and practices. Relevant technologies are generally the same across all three pollutants.

Generation replacement: This strategy involves utilizing alternatives to coal combustion, including generation based on natural gas, renewables, and nuclear energy. Relevant technologies are generally the same across all three pollutants.

Four clean technologies that indicate the wide range of costs and performance encompassed by these abatement strategies were selected as the focus of this study: for SO_2 control, precombustion coal cleaning (*fuel modification*) and FGD (*postcombustion control*); and for NO_x control, LNBs (*combustion modification*) and SCR (*postcombustion control*). For each pollutant, the former "indicator technology" is comparatively low-cost and low-performance regarding abatement, and the latter is high-cost and high-performance (see *SI Text, Technical Details* for more context, including market, cost, and performance information). Each technology has specific application either to SO_2 or NO_x control, rather than to multiple pollutants, limiting independent policy variables that could have a discernible impact on innovation patterns. Note that indicator technologies were chosen for their relevance to abatement rather than to the support of CTP operations, unlike such technologies as continuous emissions monitors and databases that ease the administrative burden of CTPs on regulators (11, 12).

Empirical research on innovation focuses on activities that sometimes overlap, including: invention; commercial adoption and diffusion; and improvements that stem from experience with a technology, such as manufacture or operations (13, 14). The allowance prices observed during the trading phases of a CTP, which reflect the aggregate effect of abatement approaches to date, shape emissions source decisions to adopt clean technologies, as well as signal innovators about potential long-term payoffs to invention. Note that before allowance prices can be observed, however, emissions sources and innovators make early investments in clean technology adoption and invention, which can be crucial for long-term success, given the relevant lead times. In the build-up to CTP operations, these early investments are shaped by *expected* allowance prices, which analysts predict based on the price and pollution-reduction potential of available abatement strategies and the challenges anticipated in emissions cap compliance.

The following section of the article presents, for both Title IV and the OTC/NBP: (*i*) the revealed difference between expected and observed allowance prices; (*ii*) the mix of abatement strategies that allowed emissions reductions to occur at observed allowance prices, including the adoption of indicator technologies; and (*iii*) commercially-oriented inventive activity in the indicator technologies, as observed in patenting activity, which is the most prominent metric of inventive output in the literature. Note that policy eras are defined here as "traditional environmental regulation" (the period before the public decision to operate a CTP), "trading preparation" (the period between the decision to operate a CTP and the onset of trading), and "trading" (the period of trading operations).

Results

Expected vs. Observed Allowance Prices. Fig. 1 shows that expected allowance prices for Title IV and the OTC/NBP generally overestimated prices observed during trading. Fig. 1 is reminiscent of the findings in other studies that a priori overestimates of the compliance costs of environmental, health, safety, and energy efficiency regulation occur frequently (15, 16). Note that Fig. 1 ends just before legal uncertainty began to surround the initially designated successor program to both Title IV and the OTC/NBP, the Clean Air Interstate Rule (CAIR), in 2008 (see the *SI Text, Policy Context* for more information).

For Title IV, even the lowest bound of expected prices overestimated observed prices for 100% of Phase I and 85% of Phase II (prices entered and surpassed the expected price range only in 2005 and 2006, with the finalization of CAIR and early unease regarding the challenges of CAIR compliance; see *SI Text, Policy Context*). By the first year of trading in 1995, it was clear that allowance prices under Title IV would be lower than expected, but the benefits of tightening the cap on SO_2 emissions would be higher because of newly recognized health risks posed by fine particles linked to SO_2 and NO_x emissions (17, 20). The program did not change to reflect this, however. Note that allowance markets were initially autarkic under both Title IV and the OTC/NBP, but became liquid over time.

When allowance prices are lower than the present value of the expected future marginal cost of compliance with a CTP, emissions sources have an incentive to bank allowances or buy additional allowances. Of the allowances generated in Title IV's Phase I, 75% were banked for future use rather than traded (Title IV allowed unlimited banking) (17). The bank generated in Phase I was so large that it was predicted in the late 1990s (21) that emissions would be able to exceed the annual allowance allocation throughout Phase II (22). These predictions proved accurate for many years. The exception occurred when trading preparation for the successor to Title IV (CAIR) began to overlap with Title IV trading, and emissions sources began early compliance actions for CAIR, encouraged by its treatment of banked Title IV allowances. [In 2005–2009, Title IV banked allowances could enter CAIR on a 1:1 basis; this ratio was set to decline to 2:1 during CAIR's Phase 1 (to begin in 2010 for SO_2) and then 2.86:1 during Phase 2 (to begin in 2015 for both SO_2 and NO_x)] (23). The EPA expected sources to reduce emissions and bank excess allowances in 2005–2009 to such an extent that during CAIR trading, emissions would exceed caps through at least 2015.

For the OTC/NBP, even the lowest bound of expected prices established during trading preparation for the OTC CTP overestimated observed prices for 70% of the OTC CTP Phase II and 82% of the NBP CTP (prices entered and surpassed the expected price range primarily during spikes in 1999 and 2003, which have

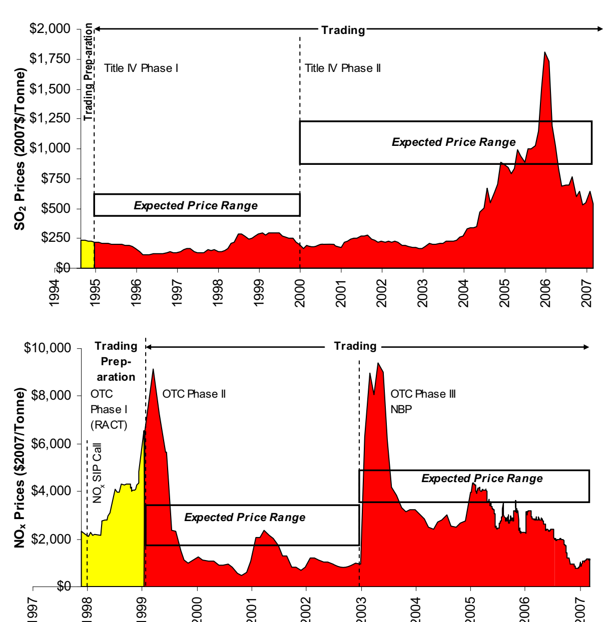

Fig. 1. The range of expected allowance prices compiled in refs. 17–19 versus observed allowance prices [see Cantor Fitzgerald (Various) Market Price Index, NY (www.cantorco2e.com)] for (*A*) Title IV and (*B*) the OTC/NBP. All prices are converted to 2007 dollars using Consumer Price Index monthly data in ref. 47.

been attributed to uncertainty regarding the advent of trading under Phase II and the transition to the NBP CTP, respectively). It is reasonable to believe that expected prices from 2003 onward would have further overestimated observed prices if analysts had known in advance of the OTC CTP that its Phase III would be superseded by the NBP CTP, and would therefore include an expanded set of states that did not start with as advanced a baseline level of NO_x control as the OTC states.

Meanwhile, allowance banking played a nontrivial role in the OTC/NBP, despite restrictions designed to minimize the chance that banked allowances might be used en masse in a given ozone season (e.g., during a hot summer) such that emissions would exceed budgeted levels. In the OTC CTP Phase II, banked allowances accounted for 20% of allowances after the first year, while in the NBP CTP they accounted for more than 10% in 2000–2003 and 2005–2007. Note that emissions never exceeded allowances during Phase II, and only did so during the NBP CTP in 2003 and 2005 (24, 25).

Adopted Abatement Strategies. For both Title IV and the OTC/NBP, an unanticipated mix of the abatement strategies of *fuel modification*, *combustion modification*, *postcombustion control*, *demand reduction*, and *generation replacement* facilitated successful compliance. This section reviews the role of these abatement strategies and highlights the contribution of the indicator technologies of precombustion control (which results in cleaned coals), LNB, FGD, and SCR. Note that the relevant technological changes reflect incremental improvements rather than radical breakthroughs, in accordance with theory (26).

Title IV. Two abatement strategies were particularly significant for SO_2 control during trading under Title IV. First, *fuel modification* accounted for about half of the emissions reductions achieved in Phase I (11, 27), largely because many emissions sources switched to naturally lower-sulfur coals (this low-capital and often cost-saving option had been important to SO_2 control in the early 1970s, before revised regulation made it impracticable; it became competitive again because of improvements in fuel blending and rail technologies that facilitated coal transport). Cleaned coals from precombustion control also played a role, with the number of operating coal preparation plants in the United States stabilizing in 1993–1997 during trading preparation and the early years of Phase I (*SI Text, Technical Details*), thereby interrupting a decline from 1982 peak levels.

Second, emissions sources balanced widespread *fuel modification* with the targeted use of *postcombustion control*, which provides high reductions at relatively high cost. Overall, however, less adoption of new FGD systems occurred during trading than had been expected during trading preparation, in part because emissions sources used FGD systems dating back to the 1970s to a greater extent than predicted (28, 29). This result disappointed the FGD industry, which had anticipated that the improved cost and performance of its systems (which emerged from technical advances made during traditional environmental regulation, particularly process chemistry developments that greatly increased system reliability; see refs. 30 and 31), would lead to higher demand for new systems under Title IV. Instead, demand for FGD systems grew during trading preparation, but declined during trading (*SI Text, Technical Details*). Furthermore, the lower-than-expected allowance prices observed during Phase I prompted cancellations of FGD orders on the order of 3,600 MW_e of planned capacity (32), which is equivalent to 19% of the FGD capacity brought online during Phase I; one cancellation even occurred after $35 million had been spent on construction (17). According to ref. 33, about one-third more FGD installations would have been adopted under a counterfactual traditional environmental regulation (i.e., a uniform emissions-rate standard) that was equivalent in its stringency to Title IV.

The other three abatement strategies played more limited roles in SO_2 control during trading under Title IV. *Generation replacement* occurred primarily because of an ongoing increase from the late 1980s in the proportion of natural gas-fired generation in the electric power sector, which had the effect of decreasing both SO_2 and NO_x emissions to some extent (*SI Text, Technical Details*). *Demand reduction* was facilitated primarily through reduced utilization of high-emitting generating facilities rather than the unsuccessful attempt to incentivize energy efficiency and renewable energy under Title IV (34). Finally, *combustion modification* occurred through the operation of sorbent injection systems by a few emissions sources.

OTC/NBP. Several abatement strategies made significant contributions to NO_x control during trading under the OTC/NBP. *Generation replacement/demand reduction* was unexpectedly important, with decreased utilization of high-emitting plants inside the capped region made possible via increased utilization of existing nuclear and natural gas-fired power plants, as well as the purchase of off-peak power from outside the capped region (25, 35).

Combustion modification also controlled NO_x emissions during trading, primarily via small-scale modifications (optimization) of existing equipment (ref. 36 estimates that this unexpectedly reduced power plant boiler emissions rates by 10–15%) and the utilization of LNBs, which performed better in the 1990s than had been expected (25, 35). Note that annual demand for new LNB installations in the United States actually declined during trading, however, in the continuation of a decline that began in 1994 (*SI Text, Technical Details*). The 1994 peak was the culmination of a demand surge that began just after the 1990 CAA addressed NO_x emissions by: (*i*) establishing a traditional environmental regulatory approach to NO_x emissions from existing sources for acid rain mitigation purposes (Phase 1 began in 1996, Phase 2 in 2000); (*ii*) requiring RACT standards (another traditional environmental regulatory approach) for nonattainment areas in State Implementation Plans and (*iii*) initiating the process that resulted in the 1994 agreement to establish the OTC CTP.

Meanwhile, demand for *postcombustion control* SCR units rose to previously unmatched heights during trading (*SI Text, Technical Details*), particularly in the non-OTC states preparing to participate in the NBP CTP in 2003. Three notes are pertinent to this rise in demand. First, the low pre-trading baseline SCR adoption rate reflects the fact that the United States did not claim that SCR was an acceptable technical basis for NO_x regulation of new sources until 1998, years after the technology had been adopted in Japan and Germany. Second, increased demand for SCR during trading did not require a corresponding decline in demand for LNBs because SCR and LNBs are not substitutes; rather, pairing the two can increase environmental effectiveness and lower costs (37). Third, the SCR demand observed during the OTC CTP Phase II was significantly lower than expected for the OTC states (17).

Finally, *fuel modification* was not a significant factor in NO_x control.

Commercially Oriented Inventive Activity. Investments in invention are bets that a given R&D direction will succeed economically in the future, when the time required for technical success has elapsed. The standard approach to empirical study of invention is to analyze technologies according to patenting activity, which is a gauge of inventive output directed toward sales in the nation issuing the patent; it is also a useful proxy for R&D expenditures, which are often difficult to obtain, particularly at a disaggregate level. The *SI Text, Technical Details* provides the particulars of constructing patent datasets for the four indicator technologies, including the approach to ensuring consistency, back-dating as close as possible to the moment of invention, and establishing the analytical frame (the patents selected were issued in the United States between January 1, 1975 and December 31, 2009, with original priority dates through December 31, 2004 and pendency periods of 20 quarters or less). The *SI Text, Technical Details* also addresses some of the potential limitations of patent analysis in this context, including issues of statistical power and appropriate counterfactuals.

Fig. 2 demonstrates that patenting activity in the four indicator technologies peaked during traditional environmental regulation and declined during trading to nadirs comparable to levels observed before the start of national SO_2 and NO_2 regulation in the United States in 1970 (38). This pattern holds across the indicator technologies, regardless of cost, performance, market trends, or unique history, and is consistent with innovators deciding during trading that their R&D investments are not worth sustaining or increasing, based on assessments of likely future market conditions under Title IV and the OTC/NBP. The *SI Text, Technical Details* upholds this pattern using different cuts of the data and considers—but dismisses—several alternative explanations, including: exogenous trends in United States patenting activity; changes in the underlying data with regard to patent classifications; a magnified influence of extranational policy events because of disproportionate representation of foreign innovators among the patent assignees; technological limits or maturity which might preclude future invention; and changes in the propensities of innovators to patent as a result of electricity sector deregulation. Note that the levels of patenting activity vary across technologies, with more complex technologies generally exhibiting higher levels of patenting. The precise timing of the observed patenting declines also varies somewhat (e.g., declines for FGD occurred throughout trading preparation and trading, declines for precombustion control and SCR occurred after a brief increase during trading preparation, and declines for LNBs occurred during trading, after increasing throughout trading preparation).

Discussion

Operating CTPs have prompted emissions sources to use a strategic mix of allowance purchases, allowance banking, and the abatement strategies of *fuel modification*, *combustion modification*, *postcombustion control*, *demand reduction*, and *generation replacement*. These CTPs have also generally had allowance prices that were lower than initially expected, according to the evidence presented here for Title IV and the OTC/NBP and elsewhere for the EU-ETS (39), RGGI (40), the United Kingdom's Emissions Trading Scheme for GHGs (41), and Southern California's REgional CLean Air Incentives Market (RECLAIM) for NO_x and SO_2 (42). Downward pressure on allowance prices is in keeping with the CTP instrument's strength in marshalling market dynamism in the service of emissions reductions. For example, it is the expected effect of encouraging a broad field of search for the adoption of abatement strategies that allow emissions sources to cost-effectively modify existing systems and practices (e.g., fuel blending advances for SO_2 control under Title IV, combustion optimization developments for NO_x control under the OTC/NBP, and so forth) Note, however, that for some CTPs, concerns have been raised about the relative role in lower-than-expected allowance prices of policy design factors such as cap stringency, allowance allocation, offsets, allowance banking, and leakage.

Regardless of the exact mix of contributory factors, the tendency to overestimate CTP allowance prices before trading—which is reminiscent of recurrent a priori overestimation of the compliance costs of traditional environmental, health, safety, and energy efficiency regulation (15, 16)—implies that early investments in clean technology adoption and invention will often turn out to be overvalued once trading begins. When this becomes clear to emissions sources and innovators, one logical effect should be reassessment of investment commitments. Supporting evidence for this has been documented in the case of SO_2 control under Title IV and for NO_x control under RECLAIM, when emissions sources chose to cancel significant in-progress clean technology installations (42, 43). Also consistent are the results above, that commercially oriented inventive

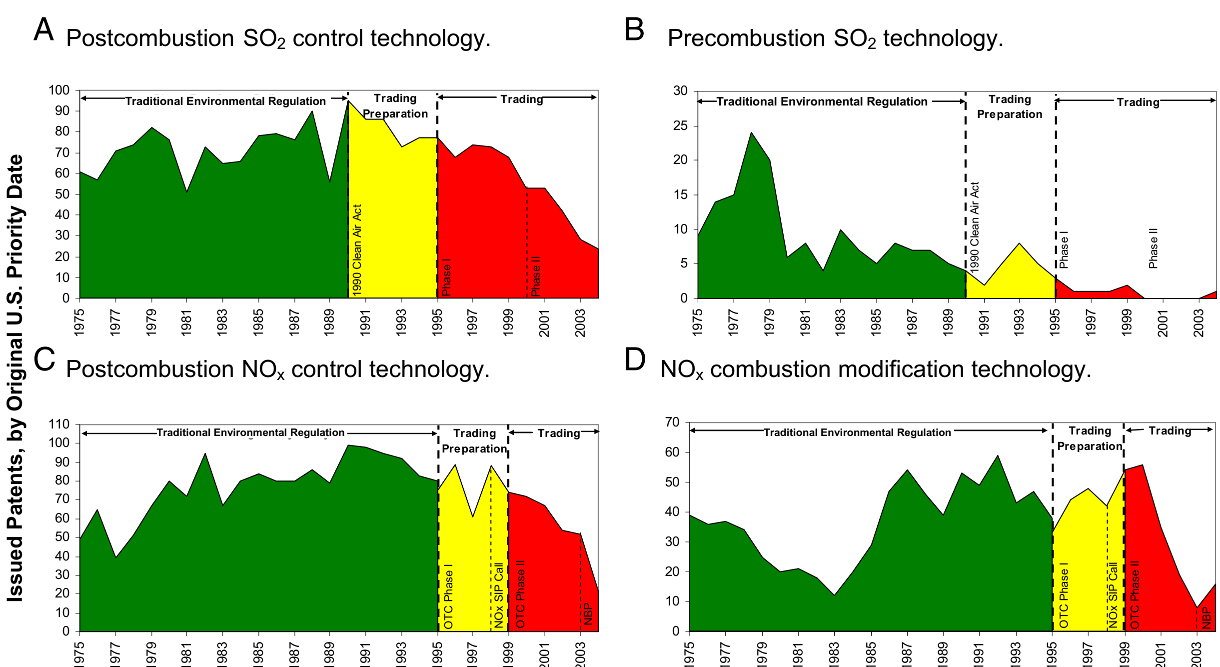

Fig. 2. (*A–D*) Patenting activity in the four indicator technologies in United States policy eras defined by traditional environmental regulation, trading preparation, and trading under Title IV and the OTC/NBP. The patents presented here were issued in the United States between January 1, 1975 and December 31, 2009, have pendency periods no greater than 20 quarters, and are depicted according to their original priority date.

activity declined during trading for SO_2 and NO_x indicator technologies of varying cost, performance, and market trends, dropping from peaks observed before the establishment of CTPs to depths a few years into trading. The implication is that CTPs do not inherently provide sustained incentives for private sector R&D investments in clean technologies, but may add to the uncertainty inherent in inventive activity. This effect is worth noting, given the likely importance for long-term climate stabilization of capturing the potential of R&D to create and improve clean technologies, as well as develop scientific personnel and organizational innovative capacity (44).

Allowance price-stabilization options (e.g., fixing prices in a predetermined range, per ref. 45, or modulating prices through an independent third-party market actor chartered to advance the public interest, and so forth) have been suggested as ways to limit the uncertainty of CTPs, including for innovators. These options are likely to pose trade-offs, however, particularly regarding the field of search for innovation, other elements of CTP design (e.g., the treatment of offsets and intertemporal allowance transfer), and complementary policy efforts with their own attributes of technology demand-pull and/or supply-push (e.g., emissions standards and public R&D support, respectively). The knowledge base necessary to characterize these trade-offs and inform climate policy efforts to incentivize the private sector to reach its innovative potential in clean technologies is still nascent, and is developing across a number of research traditions and methods (9). Synthesizing this knowledge and deepening its attention to strategic activities and behavioral issues within the "black box" of innovation (46) will aid global efforts to achieve the technological change necessary to avoid the worst impacts of climate change.

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Supporting Information

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There are three sections to this document: (*i*) an overview of the public health and environmental concerns associated with sulfur dioxide (SO_2) and nitrogen oxides (NO_x), as well as national emissions trends for SO_2, NO_x, and carbon dioxide (CO_2) in the United States; (*ii*) an overview of the policy context regarding SO_2 and NO_x control in the United States, broken up by time periods defined by traditional environmental regulation, trading preparation, and trading; and (*iii*) a discussion of the technical details of the analyses conducted for the main text.

SO_2 and NO_x Emissions

It has long been in the public interest to control emissions of SO_2 and NO_x, both for reasons of public health and environmental protection. Regarding public health, SO_2 and NO_x are eye, nose, and throat irritants. SO_2 is particularly noteworthy for its role in the infamous "killer smogs" that were fatal to 70 people in 1948 in Donora, Pennsylvania and up to 12,000 people in 1952 in London, England (1–3); these smogs were turning points in air pollution policy history. Meanwhile, NO_x is now known to be a key constituent of tropospheric (ground-level) ozone, which can worsen bronchitis, emphysema, and asthma, as well as cause lasting damage to the lungs. One species of NO_x—nitrogen dioxide (NO_2)—has been recognized as a criteria pollutant for air pollution policy in the United States since at least 1970 because of its contribution to respiratory illness and lung disease. Finally, SO_2 and NO_x are significant secondary chemical components of fine particles (2.5 μm or less), which can deposit deep in the lungs. These particles, which are connected to cardiovascular and respiratory disease, began to be a major public health concern in the 1990s.

Regarding the environment, SO_2 and NO_x are major contributors to acidic deposition ("acid rain"), with resulting damage to lakes, streams, plants, and forest growth (SO_2 plays a greater role than NO_x). This environmental problem became particularly salient in the United States in the 1980s. SO_2 and NO_x are also linked to climate change, although in complex and conflicting ways. One species of NO_x, nitrous oxide (N_2O), is a powerful greenhouse gas (GHG), and ground-level ozone is also a contributor to global warming. In contrast, aerosols, formed partially as the result of SO_2 emissions, are credited with acting to slow the speed of global warming.

Fuel combustion for electric power generation is a common significant source of SO_2, NO_x, and CO_2 emissions. Fig. S1 presents SO_2, NO_x, and CO_2-equivalent GHG emissions from this source in the United States, based on national emissions inventory data compiled by the Environmental Protection Agency (EPA). By 2008, United States emissions from fuel combustion for electric utilities declined 59% for SO_2 from their peak in 1975, and declined 57% for NO_x from their peak in 1980. Forty-two percent of the total SO_2 reduction occurred since trading began under Title IV in 1995. Sixty-eight percent of the total NO_x reduction occurred since 1999, when trading began under the Ozone Transport Commission (OTC) NO_x Budget Program (the OTC cap-and-trade program, OTC CTP) and its virtually seamless replacement and expansion, the NO_x Budget Trading Program under the EPA NO_x State Implementation Plan (SIP) Call (the "NBP CTP"; the paired CTPs are collectively titled here the "OTC/NBP"). As discussed in the policy context section below, a number of policies contributed to these declines, including, but not limited to, these CTPs.

Unlike SO_2 and NO_x emissions, CO_2-equivalent emissions from the electric power sector have been increasing since GHG inventories began to be compiled in 1990, although levels have declined a bit since 2007.

Policy Context

SO_2. ***Traditional environmental regulation (before 1990).*** The United States first regulated SO_2 emissions in the 1970 Clean Air Act Amendments (CAA), which directed the newly formed EPA to establish National Ambient Air Quality Standards (NAAQS) for SO_2 and several other "criteria" air pollutants to protect public health and welfare without consideration of economic or technical feasibility. Each state had to develop a SIP for controlling criteria pollutant emissions from *existing* stationary sources and submit it to the EPA for approval. SIPs were generally submitted in 1972. For SO_2 emissions, almost all SIPs called for continuous reduction, as opposed to tall stacks or intermittent controls. In effect, this action gave emissions sources in the electric power sector the opportunity to use low sulfur fuels, precombustion control, or flue gas desulfurization (FGD) systems for compliance.

Meanwhile, the CAA called for major *new and significantly modified* existing sources of criteria pollutants to be subject to New Source Performance Standards (NSPS), based on the EPA's determination of the adequacy of the demonstration for commercial use of relevant clean technologies. For SO_2 control, the agency determined that FGD technologies, previously adopted in Japan, had been adequately demonstrated to provide the technology basis for standard-setting in the United States. Therefore, the 1971 NSPS set a maximum allowable emission rate of 1.2 lb of SO_2/MBtu heat input (2.2 kg/Gcal), a rate that effectively required 0–85% SO_2 removal, depending on coal properties. This standard was technologically flexible, because it could be met through the use of low sulfur fuels, precombustion control, and FGD systems. The 1979 NSPS for SO_2, however, required a 70% reduction of potential SO_2 emissions from power generation based on the combustion of low-sulfur coal and a 90% reduction of potential SO_2 emissions from generation based on the combustion of high-sulfur coal. This standard was not technologically flexible because it essentially mandated that any new or significantly modified power plant would have to operate an FGD system of some type, with the system's required performance varying based on the sulfur content of the coals the plant would consume (i.e., lower-sulfur coal combustion required at least the operation of lower cost, lower performing dry FGD systems, and higher-sulfur coal combustion required higher cost, higher performing wet FGD systems; see ref. 4 for more details).

After the 1979 NSPS, growing acid rain concerns raised the importance of achieving additional SO_2 emissions reductions. In response to these concerns, more than 70 bills were unsuccessfully introduced in Congress between 1979 and the time that the CAA was revised in 1990 (5). The CTP instrument introduced in Title IV of the 1990 CAA has been credited with breaking the political logjam on acid rain legislation by providing economically interested parties with an opportunity for expression other than blocking legislation (e.g., negotiating additional allowance allocations for facilities in high-sulfur coal areas) (6). Title IV's political success has contributed to the perception that CTPs are more palatable than other environmental policy instruments in the United States. The recent experience attempting to pass national GHG CTP legislation has shaken this belief, to some extent.

Trading preparation (1991–1994). The details of Title IV were established in 1990. The first phase (Phase I, 1995–1999) was to apply to 263 existing "Table A" generating units from 110 power plants that had been grandfathered out of the NSPS. Firms would be able to voluntarily enroll additional "compensation and substitution" generating units in Phase I. (The "substitution" provision was intended to enable owners of Table A units to substitute less costly emission reductions from non-Table A units for their Table A reductions. The "compensation" provision was designed to ensure that non-Table A units that provided additional generation to compensate for reduced generation from Table A units would be included in the trading scheme). The second phase of Title IV (Phase II, 2000–2010) was to apply a cap of 8.95 million annual tons (8.06 million annual tonnes) of SO_2 to about 2,500 existing units, or all fossil fuel-fired power plants larger than 25 MWe. For both phases, emissions sources would have to demonstrate sufficient allowances to cover emissions, as judged annually in a "truing-up" period. Penalties were to be based on a 1990 fine of $2,000 per ton ($2,197 per tonne) of SO_2 above acceptable levels; fines would be adjusted for inflation (7). Allowances would be annually allocated by the EPA from a reserve that would be based on the sum of the product of each source's 1985–1987 emissions baseline and the lower of either its allowable or actual 1985 emissions rate, plus the product of each source's 1985–1987 baseline and the phased emissions rate. [The phased emissions rates were relatively modest: the rate in Phase I was slightly more than twice as lenient as the 1971 maximum allowable emission rate (NSPS) (i.e., 2.5 lb SO_2/MBtu heat input, or 4.5 kg/Gcal), and the rate in Phase II equaled that of the then 30-y-old rate (i.e., 1.2 lb SO_2/MBtu heat input, or 2.2 kg/Gcal).] All Table A units in Illinois and Indiana, as well as all but three in Ohio, were granted additional allowances for Phase I and were not subject to the reserve calculation; these same units, plus many others, were designated to receive additional allowances for Phase II [see 42 US Code 7651c(a)(3) and 7651d(a)(3)]. Secondary allowance supplies for Title IV were to come from: (*i*) an annual allowance auction each March, which was designed to help new entrants; (*ii*) opt-in allowances for units entering the program voluntarily; (*iii*) "extension" allowances to incentivize Phase I participants to reduce individual units' emissions by 90%; and (*iv*) a complex series of "bonus" allowances in Phase II [see refs. 8 and 9, and 42 US Code 7651d(a)(2)]. The largest of these secondary supplies was the annual auction, which ultimately accounted for 1.7–2.6% of the total allocated allowances each year between 1995 and 2002 (10).

This auction also served as a tool for early price discovery during trading preparation. In early 1992, the EPA announced Title IV allocations and made it possible for firms to trade and to obtain allowances via spot and forward auctions held in 1993 and 1994. The prices revealed in these pre-Phase I auctions were considerably lower than the price estimates for Phase I (Fig. 1), to the surprise of many outside observers (9). These prices are consistent with the substantial emissions reductions made during trading preparation and the early years of Phase I, however, when erroneously high allowance price expectations dominated decision-making on compliance options that either required significant lead times and "irreversible" investments, like FGD systems, or involved long-term coal contracts (11).

Trading (1995 and beyond). Fig. S2 depicts the prices for Title IV's spot and 7-y auctions, as converted to constant 2007 dollars using the Consumer Price Index (CPI) (12). The earliest data exhibited here are from the pre-Phase I auctions and the latest are from 2010, the last year of Phase II and the first year of the Clean Air Interstate Rule (CAIR) SO_2 market, which was the originally designated successor program to Title IV. The spot prices in Fig. S2 are consistent with observed prices in Fig. 1, and the 7-y prices help to characterize the long-term investor expectations of the SO_2 market.

As mentioned in the main text, when Title IV trading began in 1995, the initial firm reaction was autarkic: firms considered Title IV to be a program to comply with rather than an opportunity for gain (13). When allowance prices proved lower than expected, emissions sources chose banking over trading, to a significant extent (9), and by the late 1990s it was believed that sources would be able to emit more than the annual allowance allocation at lower-than-expected prices through the entirety of Phase II (7, 14, 15). Indeed, this pattern held until 2005 and 2006, with prices exhibiting minimal volatility that was considered commensurate with that experienced by energy markets.

In 2005 and 2006, however, prices entered and surpassed the initially expected price range for Phase II, in a price spike that has been ascribed to the finalization of CAIR and early unease regarding the challenges of CAIR compliance (see ref. 16, which also discusses other potential factors in the 2005–2006 price spike, including heightened prices for natural gas that have often been attributed to supply disruptions under Hurricanes Katrina and Rita). CAIR, which also controlled NO_x emissions, was based on the premise that nonattainment of the NAAQS for fine particles ($PM_{2.5}$) and 8-h ozone (see discussion of ozone regulation below) in the eastern United States was caused in large part by precursor SO_2 and NO_x emissions in some 28 upwind states plus the District of Columbia. First proposed as the "Interstate Air Quality Rule" on December 17, 2003 and published in the *Federal Register* on January 30, 2004, the final form of CAIR (announced March 10, 2005 and published in the *Federal Register* on May 12, 2005) established reduction targets for annual SO_2 and NO_x emissions for $PM_{2.5}$ in 23 states plus the District of Columbia, as well as for seasonal NO_x emissions for ozone in 25 states plus the District of Columbia. (Note that the seasonal NO_x program was not included in the initial proposals for CAIR, in part because of EPA analyses showing that it would be dominated by the annual NO_x program). States could either meet these SO_2 and NO_x targets by requiring power plants to participate in an EPA-administered two-phase interstate CTP, or they could adopt measures of their own choosing, with a September 2006 deadline for CAIR SIP submission. For SO_2, Phase I was to begin in 2010, and for NO_x (both annual and seasonal), Phase I was to begin in 2009; Phase II was to begin for all pollutants in 2015. To provide a "federal backstop" for the CAIR SIP process, the EPA proposed that until a state's SIP was in place, a Federal Implementation Plan (announced August 1, 2005 and published in the *Federal Register* on August 24, 2005) would require power plants in affected states to participate in separate two-phase CTPs for annual SO_2 emissions, annual NO_x emissions, and ozone season NO_x emissions, thereby mirroring the state CTP option.

Fig. S2 shows that SO_2 allowance prices declined from their December 2005 peak throughout the remainder of Phase II (prices crossed back to lower-than-expected levels for Phase II as early as September 2006). The overall post-2005 Title IV price decline coincided with the overlap between Title IV and the trading preparation period for CAIR. Emissions sources during this period engaged in significant "early action" abatement activity, which has been attributed, in large part, to incentives provided by CAIR's favorable treatment of banked Title IV allowances in this period [in 2005–2009 Title IV banked allowances could enter CAIR on a 1:1 basis; this ratio was set to decline to 2:1 during CAIR's Phase 1 (to begin in 2010 for SO_2) and then 2.86:1 during Phase 2 (to begin in 2015 for both SO_2 and NO_x)] (15). The EPA expected sources to reduce emissions and bank excess allowances in 2005–2009 to such an extent that during CAIR trading, emissions would exceed caps through at least 2015. The ultimate banks that formed during the CAIR trading preparation period for the annual SO_2, annual NO_x, and seasonal NO_x markets were even greater than expected, however.

Beyond early CAIR actions, other factors underlying the post-2005 price decline included low natural gas prices, difficult conditions in the overall economy that helped stem electric power demand, and legal uncertainty regarding CAIR. This legal uncertainty started on July 11, 2008, when the United States Circuit Court of Appeals for the District of Columbia Circuit vacated CAIR. It continued on December 23, 2008, when the same court revisited its earlier decision, remanding CAIR back to the EPA for redesign to correct its court-identified flaws, but allowing it to continue functioning in the interim. The court expressed two primary concerns about CAIR: (*i*) that trading would interfere with NAAQS compliance in downwind states; and (*ii*) that the EPA did not have the authority to change the statutorily determined formula under Title IV that defined an SO_2 allowance as representing one ton of emissions (15).

The EPA proposed a replacement for CAIR (the "Transport Rule") on July 6, 2010 (published in the *Federal Register* on August 2, 2010). For SO_2, the Transport Rule establishes two CTPs based on a stringent "group 1" set of states and a moderate "group 2" set of states, with states allowed to trade within their group; it also establishes an annual NO_x CTP and a seasonal NO_x CTP (see page 45,306 of the August 2, 2010 *Federal Register*). Unlike CAIR, the CTPs in the Transport Rule are based on state-specific, rather than regional, emissions budgets and allow only for "intrastate and limited interstate trading" based on final decisions regarding "assurance provisions" in the current proposed rule. Although allowance banking is allowed, no CAIR/Title IV allowances will be allowed to carry over into the Transport Rule programs, nor will CAIR annual or seasonal NO_x allowances be allowed to carry over. For SO_2, the primary justification for this is the issue raised by the court regarding the statutory definition of Title IV allowances (see page 45,388 of the August 2, 2010 *Federal Register*). The NO_x justification is based on concern that the large size of the CAIR allowance banks might "significantly reduce the amount of emissions reductions that would otherwise be achieved in the proposed Transport Rule NO_x programs, particularly in the earlier years (e.g., 2012 and 2013) (15)." CAIR SO_2 and NO_x allowance prices plunged in the days following the announcement of the Transport Rule.

NO_x. *Traditional environmental regulation (before 1995).* Most of the traditional environmental regulatory experience with NO_x emissions reduction in the United States relates to one species of NO_x, nitrogen dioxide (NO_2), which was first regulated as a "criteria" pollutant under the 1970 CAA. All regions of the United States comply with the annually averaged NO_2 NAAQS, which was established in 1971 and left in place through three reviews, including a relatively recent one that resulted in the creation of an additional 1-h NO_2 NAAQS on January 22, 2010, because of concern about short-term exposure to high concentrations of NO_2.

As will be detailed in the trading preparation and trading sections below, most of the CTP-related NO_x policy experience in the United States pertains to a different criteria pollutant under the CAA—ground level ozone—specifically in the context of interstate emissions transport. Traditional environmental regulation regarding ground-level ozone, which did not recognize the role of NO_x in ozone formation until the mid-1980s, began in 1971, with NAAQS for "photochemical oxidants," which used an hourly average that could not be exceeded beyond 1 h per year. This standard was weakened somewhat in the NAAQS finalized in 1979, which relaxed the 1971 0.08 ppm standard to 0.12 ppm and formally changed the chemical designation of the NAAQS from photochemical oxidants to ozone (see ref. 17 for a comprehensive review of pre-1997 ozone regulation in the United States). The ozone NAAQS has been more difficult to achieve than the annual NO_2 standard, with particularly serious attainment problems in southern California, the Texas Gulf Coast, and the Northeast (note that ozone is typically a more serious public health issue during the May–September "ozone season").

For criteria air pollutants, major new and significantly modified sources are subject to NSPS based on the EPA's judgment of whether relevant control technologies are adequately demonstrated for commercial use. During most of the history of NO_x emissions reduction in the United States, selective catalytic reduction (SCR) technology has not been credited as adequately demonstrated to serve as the technical basis for regulation, and the stringency of United States regulation has concomitantly remained fairly modest, both for the new sources covered by the NSPS, as well as for existing sources (the weakness of the NSPS has made it difficult to justify more stringent regulations for existing sources). In December 1971, the NSPS for NO_2 was published based, in part, on findings of a report that noted that unlike the "speculative" control technique of SCR, combustion modification technologies were adequately demonstrated (most of the commercial experience had occurred in California) (18). When the NSPS for NO_2 was revised in 1979, the limits shifted modestly: for coal-fired units, the shift was from 0.7 lb/MBtu (1.3 kg/Gcal) to 0.6 lb/MBtu (1.1 kg/Gcal) for subbituminous coal and from 0.7 lb/MBtu (1.3 kg/GCal) to 0.5 lb/MBtu (0.9 kg/Gcal) for bituminous coal; for gas-fired units, there was no change, with limits remaining at 0.2 lb/MBtu (0.4 kg/Gcal). The modesty of the shift between the 1971 and 1979 NSPS for NO_2 was because of a determination that Japanese experience with SCR technology in the late 1970s was taking place on units that were too small to adequately demonstrate the technology in the United States [note that at least one state, California, did not similarly dismiss Japanese experience when considering its own regulation regarding NO_x (19)]. It was only in 1998, after SCR had been installed commercially for over a decade on a total worldwide coal-fired capacity of almost 70 GWe—with Germany and Japan the leading nations—that SCR was designated as the "best demonstrated technology" to serve as the technical basis of the NSPS for power plant NO_x emissions in the United States (19). The 1998 NSPS was considered to be very late in coming, based both on statutory deadlines under the 1990 CAA and because of technological changes observed since the 1979 NSPS with regard to improvements in SCR catalyst formulations and management, as well as in engineering practices (20). The 1998 NSPS was also considered somewhat irrelevant, as most case-by-case state permitting decisions at the time already met more stringent targets, primarily because of the "Prevention of Significant Deterioration" program of the CAA (21).

Although the 1990 CAA did not include the sort of stringent regulation that would necessitate adoption of SCR technology, it was a major milestone in NO_x policy nevertheless, particularly because of its acknowledgment of the role that NO_x emissions from stationary sources play in both acid rain and ozone formation (see Title IV and Title I, respectively). The 1990 CAA addressed the NO_x acid rain issue by introducing a national two-phase, rate-based reduction program for NO_x emissions from existing sources, with Phase I beginning in 1996 (this was finalized in 1995) and Phase II beginning in 2000 (this was finalized in 1996). The rates used in the acid rain program for NO_x were modest, as in the SO_2 case, and were based on combustion modification technology in Phase I and on abatement equipment of comparable cost to combustion modification technology in Phase II (the cost emphasis for Phase II effectively ruled out SCR) (21, 22).

Meanwhile, the 1990 CAA addressed the NO_x ozone issue in two major ways. First, it established new nonattainment area classifications (marginal, moderate, serious, severe, extreme) with related deadlines for inventories and SIPs. The SIPs were required to have provisions for:

> the implementation of all reasonably available control measures as expeditiously as practicable (including such reductions in emissions from existing sources in

the area as may be obtained through the adoption, at a minimum, of reasonably available control technology [RACT]). [42 US Code 7502(c)]

(Note that the RACT standard was initially established for nonattainment areas in the 1977 CAA).

Second, the 1990 CAA gave the EPA Administrator the authority to establish "transport regions" whenever it was determined that the "interstate transport of air pollutants from one or more states contributes significantly to a violation of a [NAAQS] in one or more other states." [42 US Code 7506(a)] The responsibilities of a transport region are to "assess the degree of interstate transport of the pollutant or precursors to the pollutant throughout the transport region, assess strategies for mitigating the interstate pollution," and recommend measures to the EPA that would ensure legally acceptable plans for all of the states in the region [42 US Code 7506(b)]. In addition to providing the EPA with this authority, the 1990 CAA also established a single ozone transport region in the District of Columbia and 12 states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia); this region became officially known as the OTC in 1991. Note that the total share of NO_x emissions from electric utility fuel combustion in the United States attributed to the OTC states is provided in the final paragraph of the NO_x policy section, below.

In 1994, all of the OTC states except Virginia agreed to a Memorandum of Understanding, which established a three-phase program for reducing NO_x emissions from large combustion sources. Phase I, which began on May 1, 1995, applied the RACT standards for large stationary sources in ozone nonattainment areas year-round to all areas of the region, including those that were already in attainment (23). Phase II, which began May 1, 1999, and Phase III, which was supposed to begin on May 1, 2003, established and then increased the stringency of a nine-state NO_x CTP in the OTC during the summer ozone season, with trading allowed year-round (note that Maine, Vermont, and Virginia did not join the OTC trading program). Under the OTC CTP, the covered region had a "budget" of allowances (worth one ton of NO_x each) during the ozone season, as associated with unique compliance vintage years. Each state could allocate allowances to its sources based on its share of the overall budget. Banking was allowed, but a source could not emit at levels that would violate RACT or other emissions limit requirements, regardless of the number of allowances each source held.

To minimize the potential for banked allowances to be used to exceed budgeted emissions in a given ozone season, the OTC CTP used a system called "progressive flow control" to restrict banking (the later NBP CTP also used this system). Under progressive flow control, once the allowance bank became larger than 10% of a given year's emissions budget, a source that wanted to use banked allowances for compliance could only redeem a portion of those allowances on the basis of one allowance for each ton of emissions, with the excess redeemable at the rate of 2:1. The portion of banked allowances subject to the 2:1 requirement was set annually by the EPA, based on the amount by which the total bank exceeded the 10% threshold.

Trading preparation (between 1995 and 1998). As stationary emissions sources prepared for NO_x trading under the OTC CTP, a number of additional policy developments occurred. First, the EPA revised the NAAQS for ozone by replacing the 1979 NAAQS 1-h standard of 0.12 ppm with an 8-h standard of 0.08 ppm (this return to the more stringent parts per million limit of the 1971 NAAQS was proposed on December 13, 1996, then finalized and published in the *Federal Register* on July 18, 1997; its basis was a 3-y average of the fourth-highest daily maximum 8-h average ozone concentration measured at each monitor within an area). Second, the EPA revised the NSPS, as mentioned above under traditional environmental regulation (the NSPS revision was proposed on July 9, 1997, then finalized and published in the *Federal Register* on September 16, 1998). Third, and most importantly for the OTC CTP, the Ozone Transport Assessment Group (OTAG) conducted a policy analysis that led directly to the replacement of Phase III of the OTC CTP with the NBP CTP.

The OTAG was a committee formed by the Environmental Council of States (a national nonprofit, nonpartisan association of state environmental agency leaders) to respond to the difficulty many states foresaw in demonstrating ozone attainment by the deadline established under the 1990 CAA. The EPA agreed on March 2, 1995 to extend the attainment deadline for states that consented to both participate in a cooperative assessment of ozone transport and implement the measures that resulted from the assessment. This cooperative assessment was conducted by OTAG beginning in May 1995, with the participation of the EPA, industry representatives, environmental groups, and 37 states in the eastern part of the United States plus the District of Columbia (OTAG states included, but were not limited to, all of the participants in the OTC) (21). In November 1997, shortly after OTAG completed its assessment, the EPA proposed regional NO_x reductions covering the OTAG area in the "Ozone Transport Rule" (better known now as the "NO_x SIP Call"). The NO_x SIP Call required 22 eastern states and the District of Columbia (including all of the OTC CTP Phase II participants except New Hampshire) to submit SIPs to address the regional transport of ozone, given a budget for NO_x emissions (23, 24). In April 1998, the EPA published a supplemental rulemaking that provided the details of a "model" CTP for states to consider in implementing the NO_x SIP Call (23). The final NO_x SIP Call was published in the *Federal Register* on October 27, 1998 (for more detail, see ref. 23, which also reviews some of the relevant litigation, including the Section 126 petitions).

The NBP, established by the NO_x SIP Call, effectively replaced Phase III of the OTC; all of the OTC trading states signed on to the model CTP, which was to begin in 2003 (15). The transition from the OTC Phase II to the NBP, instead of the OTC Phase III, was managed by officially retiring OTC allowances and giving all regulated entities under the new NBP a portion of a "compliance supplement pool" (CSP) of allowances, which most OTC states apportioned in exchange for banked OTC allowances (see ref. 15 for more on the CSP, which was primarily apportioned to non-OTC states). Note that litigation delayed the implementation of the NBP for non-OTC states.

The total share of NO_x emissions from electric utility fuel combustion in the United States attributed to the OTAG and NBP states is provided in the final paragraph of the NO_x policy section, below.

Trading (1999 and beyond). By the time the OTC Phase II began in May 1999 and NO_x CTP operations could be observed, the details of the NBP that would succeed it in 2003 had been clear for several months; what was not clear was how readily utilities would be able to meet the OTC Phase II emissions cap. Allowance prices spiked beginning in mid-1998, a few months before the transition from the RACT-based OTC Phase I to the OTC Phase II CTP occurred, and then settled down to lower-than-expected levels by mid-1999, shortly after trading began (Fig. 1). According to interviews reported in ref. 25, the 1998 allowance price upswing took place because market participants thought that regulated firms had not installed enough control technology to meet the cap. Allowance prices dropped, however, when plants in Massachusetts, New Hampshire, New Jersey, and Pennsylvania quickly installed control technology, early reduction allowances began to enter the market, and litigation and a consent order delayed the entry of several Maryland sources into the market. After the initial price spike, allowance prices stabilized, remaining at lower-than-expected levels throughout the duration of the OTC Phase II. Although the allowance bank that grew during the OTC Phase II CTP was large, accounting for 20% of allowances after the first year and triggering progressive flow control for the duration of the program, annual emissions never exceeded the cap. Note that as in the Title IV case, the initial firm reaction to trading under the OTC Phase II CTP was autarkic, although the allowance market under the OTC Phase II (and later NBP) ultimately became liquid (25).

With the transition from the OTC Phase II to the NBP, another price spike occurred: allowance prices grew dramatically in the first half of 2003 and then returned to lower-than-expected levels by the latter part of that year. According to interviews reported in ref. 25, the 2003 NBP price upswing occurred because of: (*i*) regulatory uncertainty stemming from "expectations and court-issued complications" of the NBP related to litigation by newly regulated firms under the NO_x SIP Call; and (*ii*) uncertainty about the performance of control technologies. There is not universal agreement on this analysis, however; for example, ref. 16 acknowledges that these factors contributed to the 2003 price spike, but attributes a more significant role to a large contemporaneous increase in natural gas prices.

The decline in allowance prices at the outset of NBP trading in the latter half of 2003 is perhaps more noteworthy than the anticipatory increase experienced earlier in the year, however; prices dropped to levels that were lower-than-expected even for the never-realized OTC Phase III. As mentioned in the main text, the OTC Phase III only covered OTC states, not the non-OTC states covered by the NBP, which lacked trading experience, contributed a greater share of NO_x emissions from fuel combustion in electric utilities than OTC states (see analysis below), and were generally considered to be comparatively underprepared for NO_x emissions reduction. Thus, if allowance price estimates could have been made in advance of OTC NO_x trading with full information about the NBP, they would almost certainly have been higher than they were for the OTC Phase III (see Fig. 1 for the difference between expected allowance prices for the OTC Phase II and Phase III and the lower allowance prices observed for the OTC Phase II and the NBP; the sources for Fig. 1 are provided in the technical details section below). Compliance with the NBP has been attributed to modifications of existing equipment, fuel switching, and the retirement of noncontrolled units (16, 26). Note that a large bank of allowances formed under the NBP, and progressive flow control applied throughout the program. Emissions exceeded annual allowance allocations in 2003 and 2005 (27, 28).

In 2005, the EPA finalized the CAIR (see the SO_2 trading policy section above for a general discussion of CAIR, including the July 2008 vacatur of CAIR and the subsequent December 2008 reconsideration and remand of CAIR back to the EPA). Phase 1 of both the CAIR annual and seasonal NO_x CTPs began in 2009, just after the judicial remand, and the NBP therefore effectively ended in 2008. As mentioned above, the EPA did not initially propose a seasonal NO_x CTP for CAIR, as its analyses showed that such a CTP would be dominated by an annual NO_x CTP. The seasonal NO_x CTP that was ultimately included in CAIR included only slightly more stringent caps than under the NBP, and ended the progressive flow control restrictions on banked allowances. Indeed, banked allowances were allowed to carry over into the CAIR seasonal NO_x CTP on a 1:1 basis for up to roughly 50% of the cap (15). The annual NO_x CTP included in CAIR was brand new, however, and therefore could not encourage the carry-over of banked annual NO_x allowances as an incentive for early reductions. Instead, its main encouragement for early reductions was a CSP similar to that included under the NBP in the OTC Phase II transition. (Note that the total share of NO_x emissions from electric utility fuel combustion in the United States that is accounted for by the states involved in the CAIR annual and seasonal NO_x CTPs is provided in the final paragraph of the NO_x policy section, below.)

A number of additional policy developments regarding the 8-h NAAQS for ground-level ozone occurred concurrently with the CAIR trading preparation period for NO_x. In 2007, the EPA began proposing revisions to the NAAQS. In 2008, the EPA formally strengthened the NAAQS, but at a less stringent level (0.075 ppm) than its Clean Air Scientific Advisory Committee had recommended. In 2009, the EPA began reconsidering the revised NAAQS. Finally, in 2010, the EPA formally proposed strengthening the NAAQS to 0.06–0.07 ppm. These NAAQS developments should be considered in the context of discussing allowance prices at the tail end of the NBP and at the outset of CAIR.

Monthly CAIR seasonal and annual NO_x allowance prices are compiled in (15) for 2006–2009, the trading preparation period and first year of trading for these CAIR CTPs. CAIR seasonal NO_x prices exhibited a steady, declining trend during this period; in contrast, CAIR annual NO_x prices vintage 2009 were quite variable, exhibiting anticipatory spikes, a bottoming out during the period of CAIR vacatur and a rebound once CAIR was remanded. The EPA attributed this volatility to uncertainty about the adequacy of NO_x control technology dissemination before CAIR, as well as to risk aversion and thin markets (15). This uncertainty was short-lived, however, based on CAIR annual NO_x prices vintage 2010, which steadily declined in forward markets in 2009. When the EPA proposed the Transport Rule (see SO_2 policy section above) to respond to the CAIR legal situation, however, CAIR NO_x prices bottomed out dramatically, with CAIR annual NO_x prices dropping more than 50% in the days after it was announced (15). Note that the proposed Transport Rule did not allow either CAIR annual or seasonal NO_x allowances to carry over because of concern that the large size of the allowance banks that had formed under CAIR might "significantly reduce the amount of emissions reductions that would otherwise be achieved in the proposed Transport Rule NO_x programs, particularly in the earlier years [e.g., 2012 and 2013] (15)."

With so many different NO_x policy developments from 1971 to the present day, it is useful to consider the relative scope of these developments as they appeared to the NO_x control industry and its innovators. NO_x emissions from electric utility fuel combustion in the United States in 1997 provides one useful snapshot into abatement markets at the time of the NO_x SIP Call, just before trading commenced under the OTC Phase II and just after the completion of the OTAG assessment. At this time, about 12% of NO_x emissions came from the OTC region, 67% came from the NBP region, and 91% came from the OTAG region. Emissions data in 2002 provides another useful snapshot; 2002 is the most recent year for which inventory data are available, as well as the year immediately preceding the origination of CAIR. Of the total NO_x emissions from electric utility fuel combustion in the United States in 2002, 78% came from the CAIR annual NO_x market region and 70% from the CAIR seasonal NO_x market region (author's calculations from NO_x point sources in Tier-1: 01 - Fuel Combustion from Electric Utilities, as reported in ref. 29).

Technical Details

This section provides further information regarding dataset construction and analysis for the three sets of results in the main document.

Expected vs. Observed Allowance Prices. The data used to construct Fig. 1 in the main text came from several sources. Regarding expected allowance prices, Fig. 1 depicts the high and low estimates of allowance prices under Title IV and the OTC CTP that were made in advance of trading, as compiled in refs. 5, 9, and 25) and converted by the author to constant 2007 dollars using ref. 12, the CPI. Fig. 1 also depicts observed allowance prices from

Cantor Fitzgerald (Various) Market Price Index as converted to constant 2007 dollars using the CPI.

Note that the expected allowance prices in Fig. 1 are comparable snapshots—captured at the time of trading preparation—of analyst estimates of the long-term operations of these CTPs, given the imperfect information available at the time. These estimates established the strategic frame for contemporaneous investments that required important lead times, including long-term coal contracts, "irreversible" installations of FGD systems, and formal research and development (R&D) efforts to serve the SO_2 and NO_x markets with new inventions. Unfortunately, Fig. 1 does not provide an understanding of how analyst estimates changed with the advent of new information. This is a particular issue with regard to NO_x allowance prices in 2003 and beyond, which were originally estimated for the never-realized OTC Phase III rather than the NBP that actually occurred. The NBP included non-OTC states in addition to the OTC states that were originally set to be covered under the OTC Phase III; leading up to the commencement of NBP trading, there was significant concern that NO_x emissions reductions would be more difficult in the non-OTC states (see NO_x policy section above). As mentioned in the main text, it appears reasonable to believe that expected prices from 2003 onward would have further overestimated observed prices if analysts had known in advance of the OTC CTP that Phase III would be superseded by the NBP CTP.

Adopted Abatement Strategies. This section provides additional information on the five major abatement strategies (i.e., *fuel modification*, *combustion modification*, *postcombustion control*, *demand reduction*, and *generation replacement*) and the four "indicator" technologies that were discussed in the main text [i.e., precombustion coal cleaning (*fuel modification*) and FGD (*postcombustion control*) for SO_2 control; and low-NO_x burners (LNBs) (*combustion modification*) and SCR (*postcombustion control*) for NO_x control].

Table S1 demonstrates the typical pollutant removal efficiencies and costs (excluding operation and maintenance) of the four indicator technologies around the time trading began under Title IV and the OTC/NBP (30). Note that except for precombustion coal cleaning for SO_2 control, which occurs primarily at coal preparation plants, these indicator technologies are developed by vendors and implemented at power plants through the aegis of architecture and engineering firms. The table shows that these four indicator technologies represent a spectrum of costs and effectiveness regarding pollution abatement.

Fig. S3 displays the shifting role of coal and natural gas in terms of the total primary energy consumed by the electric power sector in the United States over time. As natural gas is generally a cleaner fuel than coal, the information in this figure provides insight into the abatement strategy of *generation replacement*.

Fig. S4 presents United States market data on the indicator technologies listed in Table S1, with Fig. S4 *A* and *B* relevant to SO_2 abatement and Fig. S4 *C* and *D* relevant to NO_x abatement. Fig. S4 also provides snapshots of the cumulative market share of the United States vis-a-vis the rest of the world in the indicator technologies at different policy-relevant points in time (see the bottom of each panel; data was not available for coal preparation plants). Note that Fig. S4 *A*, *C*, and *D* show the annual number of power-plant boiler units installing the indicator technology (on the same scale); Fig. S4*B* shows the number of coal-preparation plants operating on bituminous coal over the same time period. The datasets displayed in Fig. S4 *A*, *C*, and *D* are adapted from ref. 31, as updated through 2003. The dataset displayed in Fig. S4*B* was constructed for this article using primary data found in refs. 32–56; because it was not possible to construct a complete dataset, the datapoints on the figure distinguish between actual data (with triangle markers) and estimated data (with no markers).

The SO_2-related graphs in Fig. S4 show several trends. First, Fig. S4*A* shows the significance of the United States in the world market for FGD systems during the time period corresponding with traditional environmental regulation in the United States (44%), and the decline of that importance during the time periods corresponding with trading preparation (22%) and trading (14%). Second, Fig. S4*A* shows an intense demand for FGD systems just before trading under Title IV, a period dominated by erroneously high allowance-price expectations, and a strong decline in FGD adoption after trading began. As noted in the main text, published survey data show that the lower-than-expected allowance prices in Phase I of Title IV resulted in cancellations of FGD orders on the order of 3,600 MW_e of planned capacity (57), which is equivalent to 19% of the FGD capacity brought online in the United States in Phase I. FGD cancellations even occurred in a case in which $35 million had already been spent on construction (9). In addition, ref. (58) estimates that the total number of FGD installations would have been about one-third higher under a counterfactual in which a uniform emissions-rate standard, designed to achieve the same aggregate abatement as occurred under Title IV, was implemented rather than the CTP; one implication is that the United States FGD market is not saturated. Finally, Fig. S4*B* shows that the number of operating United States preparation plants peaked in 1982; its decline reversed and then held steady in the 2 y leading up to and following the introduction of Phase I of Title IV, before resuming.

The NO_x-related graphs in Fig. S4 provide several insights into the United States market for NO_x control. First, Fig. S4*C* shows the absence of the United States in the world market for SCR systems during the time period corresponding with traditional environmental regulation in the United States (2%), and how the United States' share of the world market increased during the time periods corresponding with trading preparation (8%) and trading (65%). Note that during the period of traditional environmental regulation, SCR was explicitly ruled-out as an acceptable basis for national regulation, despite the important early role played by the United States in SCR R&D in the 1970s. This situation only changed with the 1998 NSPS, after SCR technology had already become the basis of case-by-case decisions under the Prevention of Significant Deterioration program of the CAA (see the NO_x policy context section above, particularly under traditional environmental regulation). Second, Fig. S4*C* shows a strong increase in demand for SCR systems in the United States beginning in 2000, 2 y into the OTC Phase II CTP and 3 y after the details of the NBP had been announced in late 1997. Most of this demand (77%) occurred in the non-OTC states, which were preparing to participate in the NBP CTP in 2003.

Third, Fig. S4*D* shows the gradual decline of the United States in the world market for LNB systems during the time periods corresponding with traditional environmental regulation (42%), trading preparation (39%), and trading (37%) in the United States. Note that SCR and LNBs are not substitutes, so the growth in demand for SCR depicted in Fig. S4*C* does not necessitate a decline in the demand for LNBs. As discussed in more detail in ref. 59, combustion modification technologies serve as a "default" technology for firms that must adopt NO_x control measures, and their pairing with SCR technologies can increase environmental effectiveness and lower costs. Fig. S4*D* shows a dramatic increase in the United States demand for LNBs beginning roughly in 1991, just after the 1990 CAA established both: (*i*) a national two-phase, rate-based reduction program for NO_x emissions from existing sources, for the purpose of mitigating acid rain; and (*ii*) the ozone transport region that later became the OTC (recall that the Memorandum of Understanding laying out the details of the OTC program for reducing NO_x emissions from large combustion sources—including the RACT-based Phase I and the Phase II and Phase III CTPs—was not signed until 1994). LNB demand peaked in 1994 and then steeply declined, with an inflection point during trading preparation in 1997, a small rebound in 1998, and then declines during trading in 1999, 2000, and 2001. Note that the United States market for LNBs does not appear to be saturated (60).

Commercially Oriented Inventive Activity. This section focuses on dataset construction and analysis regarding patenting activity, which is analyzed in this article to consider the relationship between policy and commercially-oriented inventive activity. A patent is an exclusive right to exploit a completed invention that meets legal thresholds of novelty, usefulness, and nonobviousness in its claims, which are openly published. Patents are, by definition, a detailed, publicly available, and relatively consistent source of data on inventive output. They are also a useful international data source, as patent protection is available in many nations.

Patent analysis is the most widely used technique in the literature for the consideration of commercially-oriented inventive activity, including its relationship to exogenous events, and the technique's strengths and weaknesses are relatively well-understood (see ref. 61 for an excellent review). Patenting activity is particularly valuable to researchers as a metric of inventive output. Patenting activity also provides insight into inventor expectations of the future markets for new/improved technologies; 40–60% of the innovations detailed in patent applications are eventually used by firms, according to surveys (62–64). Finally, patenting activity is often considered by researchers to be a useful proxy for R&D expenditures, an input into inventive activity that is difficult to tabulate, particularly at disaggregated levels (for a review of the support for same-period modeling of patents and R&D expenditures, see ref. 65).

Dataset construction. Constructing patent datasets that can potentially provide useful insights into the connection between inventive activity and exogenous public policy events requires several steps: (*i*) the selection of technically relevant patents; (*ii*) the back-dating of these patents to the time of initial invention; and (*iii*) the determination of the frame to use in characterizing analytically useful trends. This section describes the steps taken to generate insights into commercially oriented inventive activity for this paper, and specifically, to derive Fig. 2 (note that Fig. 2 is based on the four indicator technologies depicted in Fig. S4 and Table S1).

Selecting technically relevant patents. Patent screening can be accomplished by searching government-issued patent classifications and by searching the text of various patent fields (e.g., the title, abstract, claims, etc.). Classification-based searching is consistently available for a much longer period than text-based searching, however, which makes it preferable to researchers interested in studying patenting trends. [In the United States Patent and Trademark Office (USPTO) system, for example, classification-based searching is available for all patents, but text-based searching of the abstract field is only consistently available for patents issued beginning in 1976.]

Patents were selected for analysis in this article if they shared the classifications used to construct the datasets analyzed in refs. 4 and 20, as compiled in Tables S2 and S3. Reliance on these classifications ensured quality, because peer-review had already validated the technical relevance of these classifications for SO_2 and NO_x abatement. Note that ref. 66 correlates with the post-combustion SO_2 control patent dataset used here at an r^2 of 0.96 and a 0.01 confidence level.

Back-dating patents to time of invention. The traditional approach to back-dating a patent to the time closest to its initial invention is to rely on its application date. However, recent evidence regarding the prominence in the USPTO of "continuing" patent applications, which receive a new application date while they add to the claims of an initial patent application, suggests that a patent's Original United States Priority Date (OUPD) is a more appropriate date to use for back-dating (67). As a result, Fig. 2 relies on OUPD as determined via ref. 67 for patents issued between January 1, 1975 and December 31, 2004, and via the commercial patent database Delphion for others. [Note that the proportion of continuing patent applications in the datasets constructed for this paper is high (29.9% of the combined SO_2 datasets and 26.8% of the combined NO_x datasets) compared with the overall USPTO (~22.7% of all USPTO patents, according to 1975–2001 data compiled in ref. 67).]

Determining the frame for trend characterization. To ensure the soundness of trend analysis regarding inventive activity and policy, a subset of the technically relevant patents determined above had to be discarded. This subsection elaborates on why the frame for trend characterization in Fig. 2 was indicator technology patents which were issued by December 31, 2009, with OUPDs through 2004 and pendency periods of 20 quarters or less. In general, these characteristics emerged in the effort to strike a balance between such analytical concerns as data consistency, statistical power, policy signal clarity, and a consideration of confounding factors.

Concern for dataset consistency drove the focus on issued patents in the USPTO, as opposed to patent applications that may or may not have been issued after USPTO review. Although patent applications should provide a more precise measure of overall levels of inventive activity, they are not consistently available in the United States over time for two reasons. First, before the American Inventors Protection Act (AIPA) came into effect on November 29, 2000, United States patents were not made public until after they were accepted and issued following a full "pendency" period, so nonissued applications before this date are not accessible. Second, AIPA, which harmonized the United States with world patent law under the Patent Cooperation Treaty, exempts applications that are only seeking protection in the United States from its requirement that United States applications, going forward, be published within 18 mo. Because there is no straightforward way to identify how large the subset of United States-only patent applications is at any given point in time, this raises concerns about the comprehensiveness and consistency of patent application data after AIPA entered into force.

Concern for dataset consistency also made it important to understand the pendency period variability of the patents to be analyzed in Fig. 2. Because patent applications that will be—but are not yet—issued are not identifiable before they are fully reviewed at the end of their pendency period, counts of issued patents back-dated to their "priority years" (the year of the OUPD) may be artificially low for certain priority years in a time-series (this is expected to be a greater problem in more recent priority years because there is less time available for review before issuance). If pendency lag distributions do not vary significantly year-to-year, however, it might be possible to determine a statistically acceptable correction function for the counts in various priority years. Unfortunately, Fig. S5 and the Kolmogorov–Smirnov test demonstrated that the pendency lag distributions for the four indicator technologies—as characterized by the number of days, grouped by quarters, between the OUPD and the date of issuance for all of the patents in a given priority year—cannot be treated the same for the purposes of constructing a correction function. Instead, a pendency period "cut-off" had to be derived for the full time-series of issued patent counts to ensure consistency.

The pendency period cutoff for issued patents to be included according to priority year in Fig. 2 was determined to be 20 quarters or less, which represents the difference between December 31, 2009 and December 31, 2004. Note that when the analysis was most recently updated for this paper, the close of

2009 was the most recent for which the USPTO provided overall trend data for issued patents back-dated to their application dates (as the best proxy the USPTO provides for the initial time of invention). It was determined that this should, therefore, be the most recent date for which issued SO_2 and NO_x-related patents should be considered in Fig. 2, because it allowed for full cross-trend comparison. (Fig. S6 shows that SO_2 and NO_x-related issued patents by application date do not simply mirror overall trends in the USPTO through 2009, although they are very similar to the Fig. 2 trends of issued patents by OUPD with the pendency period cutoff). Meanwhile, the close of 2004 is the most recent before the finalization of CAIR, a policy development that complicated the signals for SO_2 and NO_x abatement [see the policy context section above; note that even widely anticipated policies have been shown to spur commercially oriented inventive activity in SO_2 control (68)]. It was determined that 2004 should, therefore, be the most recent priority year for which the impetus to invent in SO_2 and NO_x abatement in response to policy should be considered. Note that Fig S7 shows that the 20-quarter pendency cutoff trends in Fig. 2 fit extremely well against similar trends without pendency period cut-offs.

Trend Analysis. The trend analysis for Fig. 2 had to cope with certain limitations. First, statistical power was a concern, with only about two decades of consistent annual count data to consider. Although this posed a serious constraint for inference, a descriptive analysis of the trends in Fig. 2 was informative in conjunction with a consideration of complementary results regarding adopted abatement strategies and expected versus observed allowance prices. Second, appropriate counterfactuals were a concern, as they are for any study of the relationship between policy and trends in inventive activity. The article's research design coped with this by focusing on a single nation that experienced a mix of policy instruments, including CTPs, for the control of two different air pollutants over time, as well as on patenting activity in a range of abatement strategy "indicator" technologies that varied in cost and performance. This approach avoided the complications inherent in alternative research designs, such as a cross-national comparative patenting study that would be subject to the muddling influence of both international patenting patterns and country-specific domestic policy idiosyncrasies (ref. 60 addresses several of these issues), or a cross-technology comparative study that would require the identification of appropriately analogous technologies that emerged under policy conditions that mimic the complicated policy context discussed above, with the exception of the CTP instrument.

The trend analysis also had to consider whether alternative explanations might account for the observed variation. Several alternative explanations were pursued and ultimately dismissed. First, as mentioned above, Fig. S6 shows that the indicator technology patent trends are not simple reflections of overall trends in the USPTO. Second, the indicator technology trends are not explained by changes in the underlying data with regard to patent classifications: all of the new and former classes that emerged from the small number of changes that did occur are captured in Tables S2 and S3. [Note that these changes, according to the Classification Order Index and archived Classification Orders, occurred in 1992 (October 6, establishing the SO_2 relevant 423/242.1–0.7, 243.01–12, 244.01–11 while abolishing the SO_2 relevant 244.00) and 1993 (September 7, establishing the NO_x relevant 423/239.1–0.2 while abolishing the NO_x relevant 423/239.0).] Third, the indicator technology trends are not simply explained by the behavior of foreign inventors who might be responding to extranational policy events, as Fig. S8 shows that the trends in Fig. 2 are retained when foreign patent holders ("assignees") are removed. Fourth, the declines observed in patenting activity across indicator technologies are highly unlikely to be explained by all four technologies reaching physical limits at about the same time, beyond which invention would be difficult to sustain, given the technical differences between the technologies. Fifth, the cross-technology patenting activity declines are unlikely to be explained by technological maturity, both for similar reasons of improbability given differences among the indicator technologies, and because the literature does not support the idea that technological maturity precludes technological opportunity for invention [see the "last gasps" phenomena observed by economic historians in cases like sailing ships, typesetters, and ice fishing (69–73)]. Finally, the observed patenting activity declines are not likely to be explained by any changes in the propensity to patent that might be brought on by coincidental United States utility deregulation trends, as such propensities should be strengthened, rather than diminished, by these trends (see discussion in ref. 74), although this merits further research.

Emissions Sources and Invention. This section presents the details of an ancillary analysis of the proportion of patents held by emissions sources in several clean technology areas that are either directly or indirectly relevant to CO_2 abatement in the electric power sector. This analysis was motivated by the question of whether the additional uncertainty in R&D decision-making under CTPs might be countered, to some extent, by a disproportionate role for emissions sources in invention in clean technologies, given that emissions sources under a CTP have more certain information regarding the likely future market for new or improved technologies than other organizations.

To conduct this analysis, several previously published patent searches were compiled and used to construct datasets that were then coded by assignee type. Patents for the *postcombustion control* abatement strategy of carbon capture and storage came from ref. 75. Patents for the *generation replacement* strategies of solar photovoltaics, solar thermal electric power, and wind power came from refs. 19 and 76. Patents for the *demand reduction* strategy of solar water heating came from ref. 76. Finally, patents for SO_2 and NO_x control came from Tables S2 and S3 and emphasize *postcombustion control*. The assignee types used in coding were: (*i*) "oil company"; (*ii*) "utility," which includes the utility industry's research consortium, the Electric Power Research Institute, Inc.; (*iii*) "transport and affiliated" firms; (*iv*) "research institutions," which include universities and government; and (*v*) "other firms and individuals," which do not include emissions sources. Coding was conducted using ref. 77, initially via a four-person team with some overlap for purposes of interrater reliability, with a final round of coding conducted by one researcher.

Fig. S9 displays the results. The category of "other firms and individuals" (i.e., not emissions sources) clearly dominates patenting across these clean technologies, accounting for 72–91% of the relevant intellectual property ownership. In contrast, emissions sources (i.e., the combination of oil companies, utilities, and transportation-affiliated firms) hold only 3–18% of the relevant patents, with utilities alone owning 0–12% of the relevant intellectual property. Thus, the evidence does not appear to support any countering of R&D investment uncertainty under CTPs on the basis of the role of emissions sources as inventors of clean technologies.

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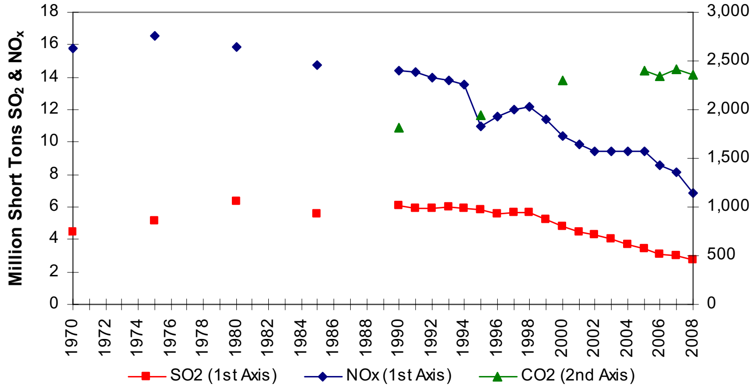

Fig. S1. United States emissions of SO_2, NO_x, and CO_2-equivalent from fuel combustion for electric utilities (1, 2).

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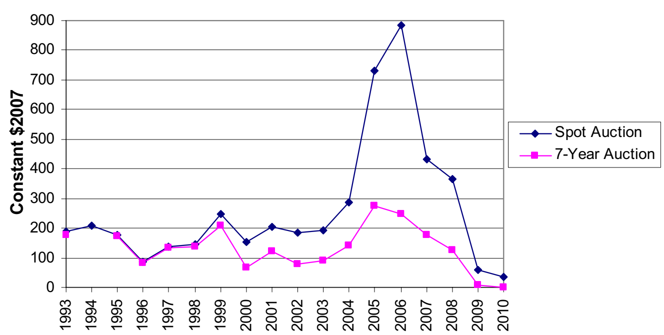

Fig. S2. Auction prices for allowances under Title IV, as converted to 1995 constant dollars (1).

1. http://www.epa.gov/airmarkets/trading/auction.html. Accessed January 11, 2011.

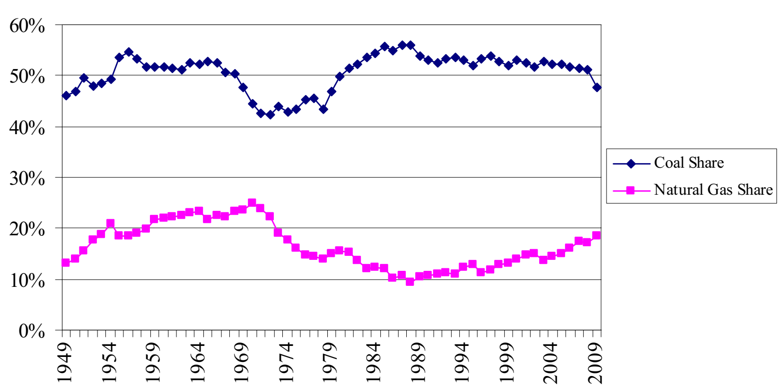

Fig. S3. Comparative share of electric power sector fuel consumption of natural gas versus coal from 1949 to projected 2009 levels (1).

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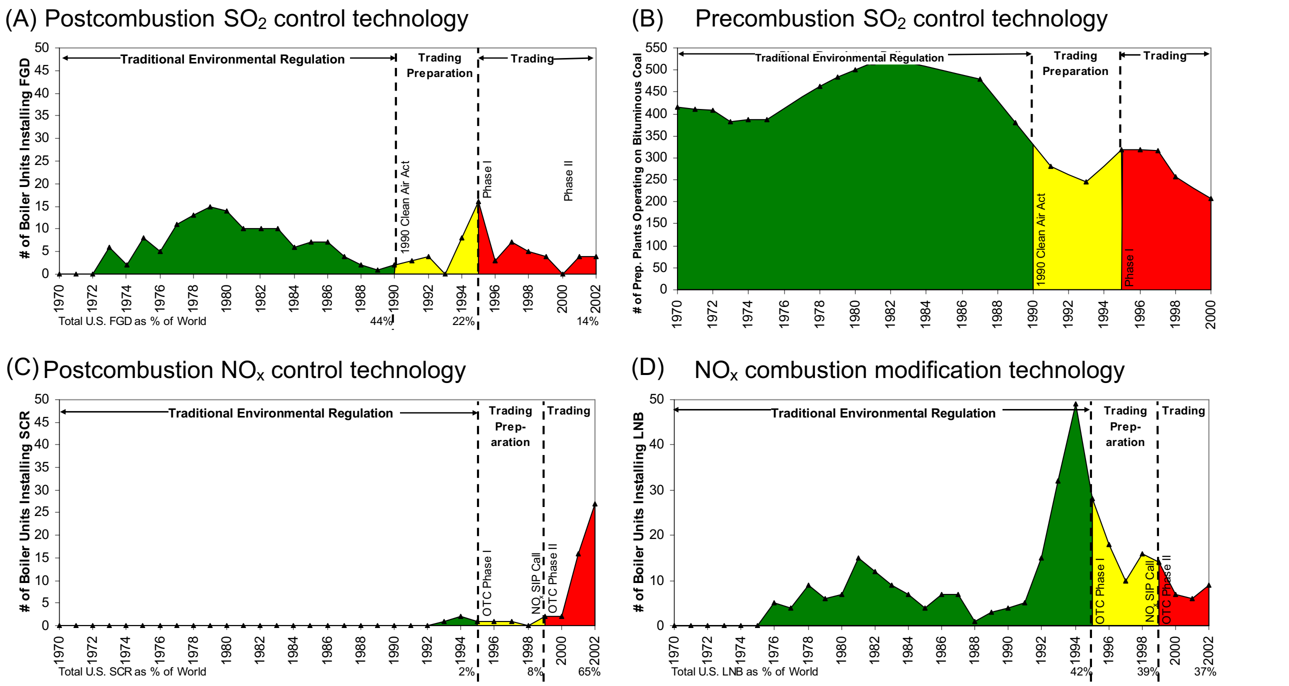

Fig. S4. United States market data for the four indicator technologies for abatement of SO_2 and NO_x emissions from power plants. (*A*) Postcombustion SO_2 control technology. (*B*) Precombustion SO_2 technology. (*C*) Postcombustion NO_x control technology. (*D*) NO_x combustion modification technology.

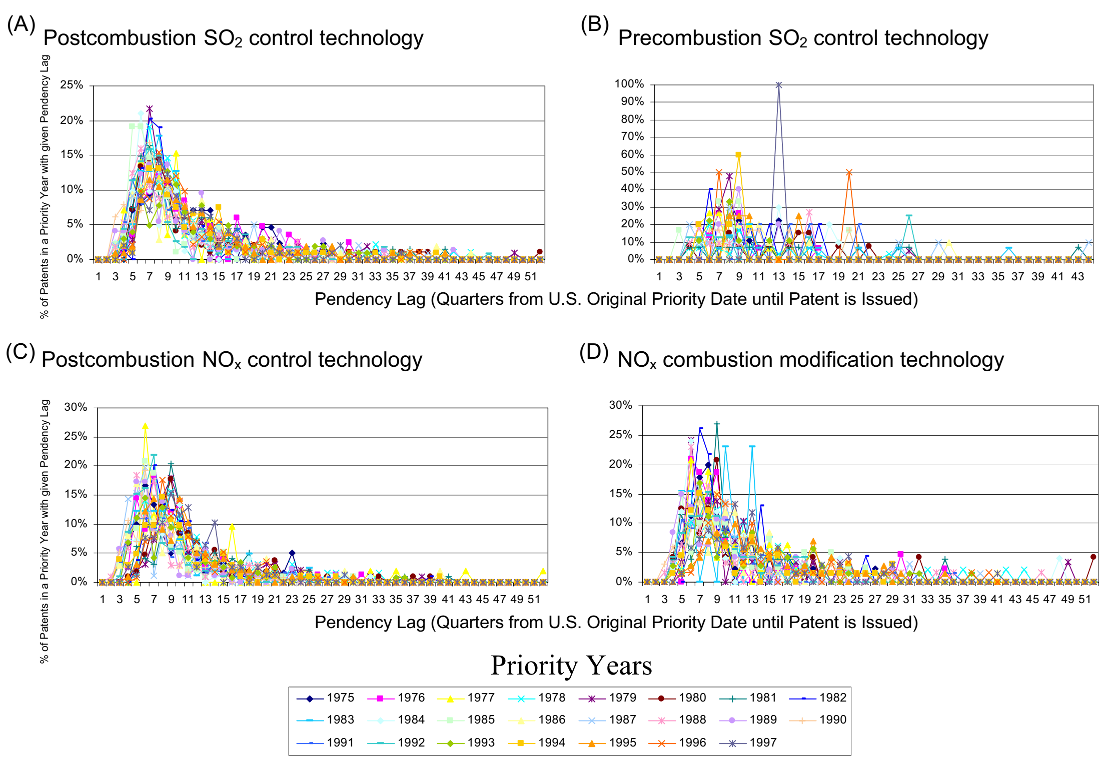

Fig. S5. (*A*–*D*) Pendency distributions for patents in the four indicator technologies.

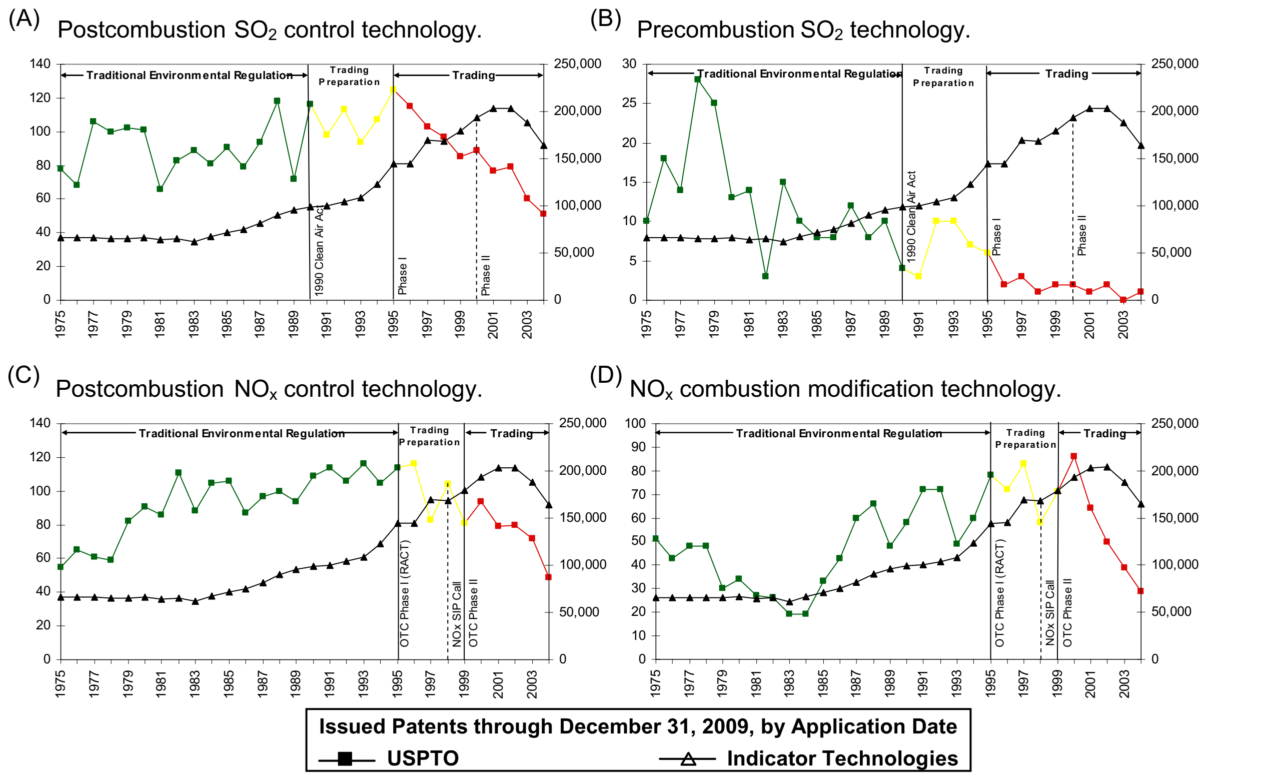

Fig. S6. Activity in the four indicator technologies and in the overall USPTO for patents issued by December 31, 2009 with application dates between 1975 and 2004. Patents are plotted on two *y* axes, with the indicator technology on the left axis and the overall USPTO on the right axis. (*A*) Postcombustion SO_2 control technology. (*B*) Precombustion SO_2 technology. (*C*) Postcombustion NO_x control technology. (*D*) NO_x combustion modification technology.

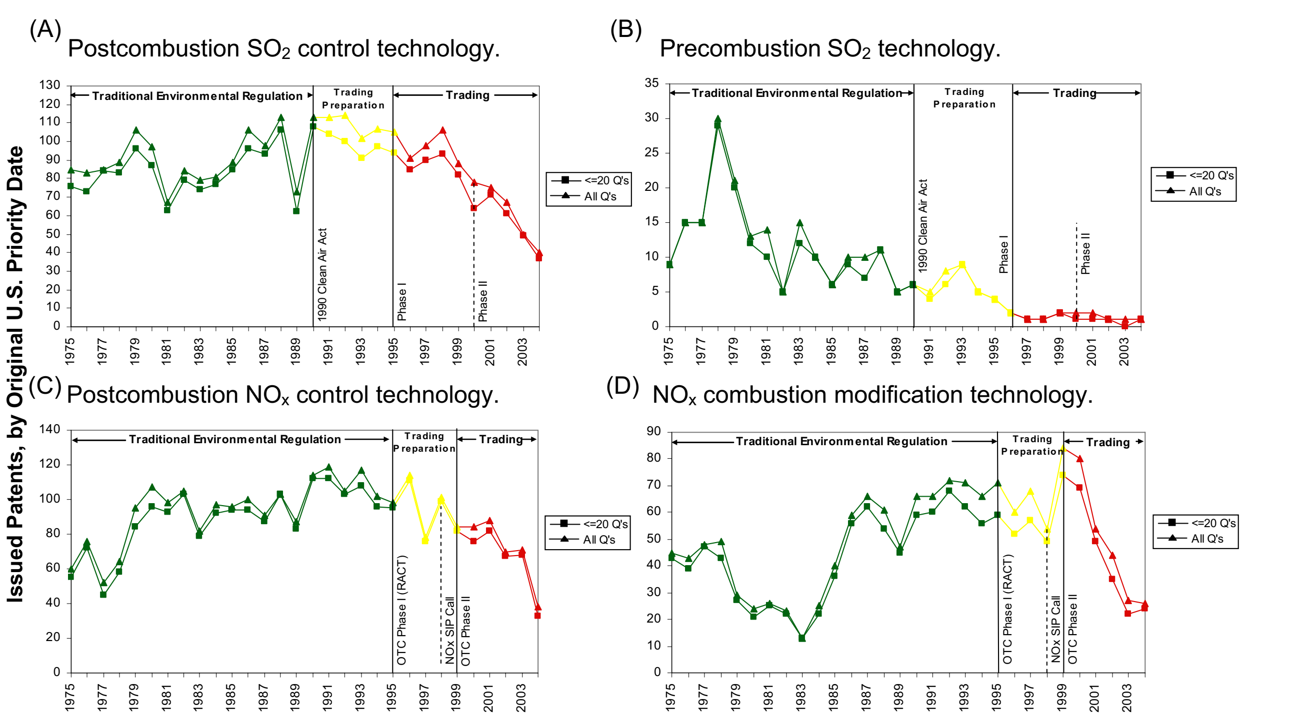

Fig. S7. Counts of all patents versus patents with pendency of 20 quarters or less in the four indicator technologies, according to the original United States priority dates of patents issued through December 31, 2009. (*A*) Postcombustion SO_2 control technology. (*B*) Precombustion SO_2 technology. (*C*) Postcombustion NO_x control technology. (*D*) NO_x combustion modification technology.

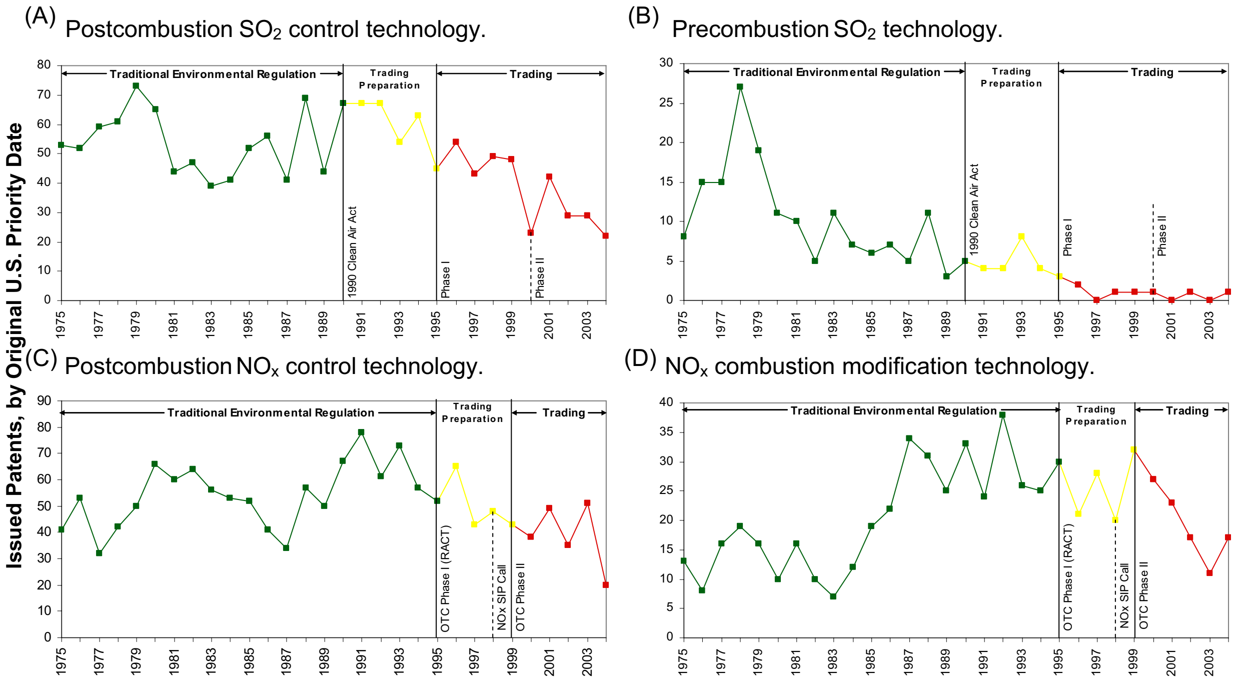

Fig. S8. Counts of patents held by United States assignees in the four indicator technologies, according to the original United States priority dates of patents issued through December 31, 2009 with pendency periods no greater than 20 quarters. (*A*) Postcombustion SO_2 control technology. (*B*) Precombustion SO_2 technology. (*C*) Postcombustion NO_x control technology. (*D*) NO_x combustion modification technology.

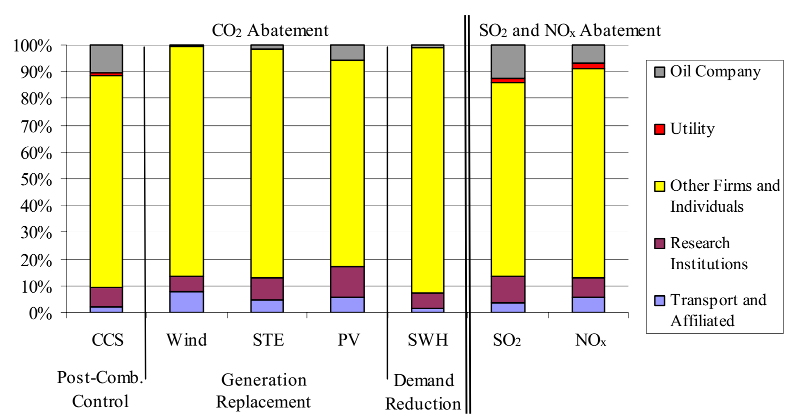

Fig. S9. Clean technology patent breakdown by type of assignee.

Table S1. Background on the four indicator technologies for abatement of SO_2 and NO_x emissions from power plants

				Capital cost	
Pollutant	Reduction strategy	Dominant technology	% Removed	New ($/kW)	Retrofit ($/kW)
SO_2	Postcombustion	FGD (“scrubbers”)	90–99	70–150	100–150
	Precombustion	Physical coal cleaning (in preparation plants)	10–40	2.9–14.3, assuming 500 MW plant burns 1,430,000 tons coal/yr at 1–5 $/ton coal	Same as new
NO_x	Postcombustion	SCR	50–95	50–100	Same as new
	Combustion modification	LNB	40–60	1–3	5–10

Adapted from ref. 30.

Table S2. USPTO classes and subclasses that comprise the SO_2 datasets

USPC class/subclasses	Definition of USPC class/subclasses
423/242.1–244.11	Class 423, the "chemistry of inorganic compounds," includes these subclasses representing the modification or removal of sulfur or sulfur-containing components of a normally gaseous mixture.
095/137	Class 095, "gas separation processes," includes this subclass representing the solid sorption of sulfur dioxide or sulfur trioxide.
110/345	Class 110, "furnaces," includes this subclass representing processes to treat fuel combustion exhaust gases, for example, to control pollution.
44/622–5	Class 044, "fuel and related compositions," includes these subclasses to treat coal or a product thereof to remove "undesirable" sulfur.

USPC, United States patent classification.

Table S3. USPTO classes and subclasses that comprise the NO_x datasets

USPC class/subclasses	Definition of USPC class/subclasses
423/235, 239.1	Class 423, the "chemistry of inorganic compounds," includes these subclasses representing: (235) the modification or removal of nitrogen or nitrogenous components of a normally gaseous mixture, (239.1) including through use of a solid sorbent, catalyst, or reactant.
122/4D	Class 122, "liquid heaters and vaporizers," includes this subclass for miscellaneous boilers and boiler parts that are not otherwise classifiable.
110/345, 347	Class 110, "furnaces," includes these subclasses representing: (345) processes to treat combustion exhaust gases, for example, to control pollution and (347) processes related to the burning of pulverized fuel.
431/4, 8–10	Class 431, "combustion" includes these subclasses representing a combustion process or burner operation that includes: (4) feeding an additive to a flame to give it a special characteristic; (8) flame shaping or distributing components in a combustion zone; (9) whirling, recycling, or reversing flow in an enclosed flame zone; (10) supplying a distinct stream of an oxidzer to a region of incomplete combustion.